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Transportation Accident Risks in the Nuclear Power Industry 1975-2020

Holmes and Narver, Inc, Anaheim, Calif Nuclear & Syst Sci Group

Prepared for

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TRANSPORTATION ACCIDENT RISKS IN THE NUCLEAR POWER INDUSTRY

1975-2020

Prepared for

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FOREWORD

More than two years ago, a study was undertaken by Holmes & Narver, Inc., for the Office of Radiation Programs, U. S. Environmental Protection Agency, to quantitatively assess the potential impact of the transportation of radioactive materials associated with the nuclear power industry through the year 2020. Preliminary publication of the results of the analyses was made in August 1973, to make the information available as a resource to the scientific community and the public generally. Comments were solicited from interested parties. The comments received were incorporated into the analyses in this report submitted to the Environmental Protection Agency in fulfillment of Contract No. 68-01-0555 by the Nuclear & Systems Sciences Group of Holmes & Narver, Inc. The work was completed in November 1974.

ABSTRACT

A quantitative assessment was made of the accident risks associated with the transportation of radioactive material in the nuclear power industry in the year 2020. A scenario was developed for the period from 1975 to 2020 for shipments between nuclear reactors, chemical reprocessing plants, fuel fabrication facilities and waste repositories. Technical data from numerous sources were collected for shipments of spent fuel, recycled plutonium, high-level radioactive solid waste and fission-product gases. Assumptions were developed regarding transport modes, shipping containers, transport pathways for dispersion of released radioactivity, population distribution and health responses to radiological exposure.

Fault tree analysis was used to estimate the probability of release from shipping containers taking into consideration the transport mode, severity of the accident and damage to the package. Estimates were made of the fraction of the radioactive contents which could be relased as a result of each class of accident. Calculations were made of the annual frequency of accidents and the frequency of radiological releases. Risks were characterized by the probability of release and the magnitude of the resulting exposure. Both individual exposure and population doses were calculated.

The results of the study indicate that by 2020 the number of shipments exceed 17,000 per year with a total shipping distance of more than 17 million miles. As a result, the number of accidents is in excess of 20 per year. However, the frequency of release is small, the expected value being less than one per 13 years in 2020. Releases from accidents involving spent fuel dominate the release frequency during the entire period studied.

The average annual population dose from transportation accidents of the nuclear power industry is insignificant--less than one person-rem per year from all sources in 2020. A release, if it should occur, is most likely to result in a relatively small exposure to individuals near the accident, on the average not exceeding the thresholds postulated for biological effects. The resulting population dose is a very small fraction of the annual natural background population dose received by all persons in the vicinity of the accident. Only in the worst and most unlikely cases of release can lung exposure exceed thresholds for biological effects. The probability of any such event is estimated at one per 90 thousand years or less. It is concluded that it is possible to operate an expanded nuclear power industry with no significant risk from transportation accidents.

This report was submitted by the Nuclear & Systems Sciences Group of Holmes & Narver, Inc., to the Office of Radiation Programs, Environmental Protection Agency, in fulfillment of Contract No. 68-01-0555. Work was completed as of November 1974.

CONTENTS

Section		Page
I	SUMMARY AND CONCLUSIONS	1
II	RECOMMENDATIONS	4
III	STUDY PLAN	5
	Introduction	5
	EPA Objectives for the Study	5
	Study Methodology	6
	Elements Included in the Study	9
	Organization of Study	11
IV	THE UNITED STATES NUCLEAR INDUSTRY	12
	Introduction	12
	Population Growth in the United States	14
	Demand for Electricity in the United States	14
	Nuclear Supply of Electricity	16
	Nuclear Fuel Cycles	19
V	NUCLEAR TRANSPORTATION FORECASTS (1977 to 2020)	30
	Annual Fuel Requirements	30
	Annual Spent Fuel Transportation	30
	Annual Plutonium Transportation	42
	Annual Transportation of High Level Radioactive Solid Waste	50
	Annual Transportation of Gaseous Fission Products	57
	Summary	61
VI	TRANSPORTATION ACCIDENT RISKS	63
	Introduction	63
	Accident Probability and Severity	64
	Containment Failure in Shipment Accidents	67
	Calculations of Release Probabilities	84

CONTENTS (continued)

Section		Page
VII	CONSEQUENCES OF RADIOACTIVITY RELEASES	91
	Introduction	91
	Release Fractions	92
	Dispersion of Radioactivity	94
	Health Effects of Radiation Exposure	99
VIII	RISKS FROM TRANSPORTATION ACCIDENTS	103
	Introduction	103
	Accident Frequency	103
	Individual Exposures	108
	Population Doses	111
	Health Effects	117
IX	REFERENCES	120

FIGURES

Figure		Page
1	Overall Organization of Evaluation of Risk from Transportation Accidents in the Nuclear Power Industry	7
2	Detailed Organization of Evaluation of Risk from Transportation Accidents in the Nuclear Power Industry	8
3	Projected Nuclear Electric Capacity	13
4	Projected Electricity Demand	17
5	Projection of Generating Capacity of Various Nuclear Reactor Types	18
6	Schematic Fuel Cycle Diagram for Light Water Reactor	20
7	Material Flow in Typical LWR Fuel Cycle Without Plutonium Recycle	24
8	Material Flow in Typical LWR Fuel Cycle With Plutonium Recycle	26
9	Material Flow in Typical HTGR Fuel Cycle	27
10	Material Flow in Typical LMFBR Fuel Cycle	28
11	Projection of Annual Nuclear Fuel Fabrication Requirements	32
12	Projection of Annual Nuclear Fuel Reprocessing Requirements	33
13	Projection of High-Level Radioactive Solid Waste Shipping Requirements	52
14	Summary of Annual Transportation Activity	62
15	Schematic Diagram of Spent Fuel Shipping Container	70
16	Schematic Diagram of Recycled Plutonium Shipping Container	70
17	Schematic Diagram of High Level Radioactive Solidified Waste Shipping Container	72
18	Schematic Diagram of Fission Gas Shipping Container	72

FIGURES (Continued)

Figures		Page
19	Fault Tree Diagram for Spent Fuel Shipping Container	74
20	Fault Tree Diagram for Plutonium Shipping Container	75
21	Fault Tree Diagram for Solid Waste and Noble Gas Shipping Containers	76
22	Frequency of Transportation Accidents	104
23	Frequency of Transportation Accident Releases	106
24	Annual Whole Body Population Dose	113
25	Annual Lung Population Dose	114
26	Annual GI Tract Population Dose	115
27	Annual Thyroid Population Dose	116

TABLES

Table		Page
1	Projected Population of the Conterminous United States	15
2	Forecast of Nuclear Generating Capacity	16
3	Annual Production of Fabricated Fuel	33
4	Annual Discharge of Spent Fuel After Cooling	34
5	Assay of Nuclear Fuels at Time of Reprocessing	35
6	Typical Radioactivity in Fuel and Wastes at Fuel Reprocessing Plants	36
7	Radioactivity of Annually Transported Spent Fuel	38
8	Spent Fuel Shipment Capacities	39
9	Spent Fuel Transportation Scenario	40
10	Distances Between Nuclear Power Reactors Operating in 1970 and Known Chemical Process Plant Sites	41
11	Distances Between Sea Ports for Spent Fuel Shipments	42
12	Summary of Annual Spent Fuel Shipping Data	43
13	Annual Plutonium Generation in Chemical Reprocessing Plants	44
14	Specific Activity of Plutonium	46
15	Radioactivity of Annually Transported Plutonium	46
16	Plutonium Shipment Capacities	47
17	Plutonium Transportation Scenario	48
18	Distances Between Chemical Reprocessing Plants and Fuel Preparation Plants in 1973	49
19	Summary of Annual Plutonium Shipping Data	50
20	Annual Transportation Requirements for High Level Radioactive Solid Waste	51
21	Radioactivity of Annually Transported High-Level Radioactive Solid Waste	54

TABLES (Continued)

Table		Page
22	Shipment Capacities for High-Level Radioactive Solid Waste	55
23	Distances Between Chemical Processing Plants in 1973 and Possible Federal Waste Repositories	56
24	Summary of Annual Shipping Data for High-Level Radioactive Solid Waste	56
25	Radioactivity of Annually Transported Noble Gas	58
26	Shipment Capacities for Noble Gas	59
27	Summary of Annual Shipping Data for Noble Gas	60
28	Probabilities of Accidents	64
29	Accident Frequency Statistics	65
30	Accident Severity Classes	66
31	Conditional Probabilities of Impact, Puncture, and Fire	68
32	Fault Tree Input Data for Spent Fuel Shipping Container on Truck	77
33	Fault Tree Input Data for Spent Fuel Shipping Container on Rail	78
34	Fault Tree Input Data for Spent Fuel Shipping Container on Barge	79
35	Fault Tree Input Data for Plutonium Shipping Container on Truck	80
36	Fault Tree Input Data for Plutonium Shipping Container on Rail	81
37	Fault Tree Input Data for Shipping Container of High Level Radioactive Solid Waste or Noble Gas on Truck	82
38	Fault Tree Input Data for Shipping Container of High Level Radioactive Solid Waste or Noble Gas on Rail	83
39	Selected Release Sequences for Spent Fuel Shipping Container	85

TABLES (Continued)

Table		Page
40	Selected Release Sequences for Plutonium Shipping Container	86
41	Selected Release Sequences for High Level Radioactive Solid Waste or Noble Gas Shipping Container	87
42	Release Probabilities for Shipping Containers	89
43	Release Probability for Adopted Transportation Scenario	90
44	Release Fractions in Transportation Accidents	95
45	Dose Coefficients	97
46	Average Population Density	99
47	Acute Effects of Radiation Exposure	100
48	Delayed Somatic Effects of Radiation Exposure	102
49	Average Annual Release of Radioactivity	107
50	Average Annual Individual Doses at 0.1 Mile	109
51	Conditional Individual Doses at 0.1 Mile	110
52	Worst Case Individual Doses in 2020 at 0.1 Mile	112
53	Conditional Population Doses in 2020	118
54	Delayed Somatic Effect of Population Doses in 2020	119

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SECTION I

SUMMARY AND CONCLUSIONS

The nuclear power industry is expected to grow rapidly during the next 50 years and thus the concomitant transportation activity also will increase. Associated with the transportation of radioactive materials is a risk of the possible release of radioactivity from accidents occurring during transport. This radiological risk will increase with the growth in total transportation of nuclear fuels and other radioactive materials of the nuclear power industry. The purpose of this study was to assess risks to the public from the accidental release of radioactivity during transportation of radioactive materials in the nuclear power industry to the year 2020.

The usual method of calculating risks is to use information based on statistical records. However, little experience exists on transportation accidents for shipments of radioactive materials from nuclear power facilities because the number of shipments to date has been small and the probability of an accident during transportation is low. Nevertheless, it is possible to estimate the risk by a process of synthesis, because shipments of radioactive material in the nuclear fuel cycle are not fundamentally different from shipments of other hazardous materials transported in routine commerce. In this study, the amount of damage, as a result of an accident to a container used for the shipment of radioactive materials, was synthesized by consideration of the design of the container and the severity of the accident. Fault tree analysis was used to obtain quantitative estimates of the release probability resulting from an accident.

The general definition of risk used in this study takes into account both the probability of occurrence of an undesirable consequence and the magnitude or value of the consequence. The risk of a specific consequence is the probability of weighted sum of all events leading to the consequence, i.e., the expected value or average. The consequences evaluated in this study were radioactivity released, population doses and public health effects.

Assumptions were made about the timely introduction of plutonium recycling programs, breeder reactors, fuel reprocessing and fabrication facilities, and waste disposal management in order to quantitatively describe the magnitude and rate of growth of the nuclear economy from 1975 to 2020. Spent fuel, plutonium, high-level radioactive solid waste, and fission-product gases were chosen as the radioactive materials requiring transportation. The transportation modes considered were trucks, rails, and barges. Five parameters were evaluated: frequencies of accidents from accident statistics; frequencies of releases from fault tree analysis;

amounts of radioactivity released from postulated release fractions; individual and population doses from an environmental dispersion model; and public health consequences from a health effects model. The results are presented as annual averages, i.e., averaged over the variety of transportation modes, accident severities and package damage severities, and as worst-cases for accidents which occur very infrequently.

As a result of the assumptions made regarding the growth of the nuclear power industry, the transportation activity will increase each year during the entire 50-year period. Nuclear power transportation activity will exceed one million miles in 1980 and ten million miles after 2000. By 2020, there will be 37,000 shipments per year averaging 470 miles per shipment - a total shipping distance of more than 17 million miles per year.

The probability of an accident occurring in commercial transportation is small. Based on current accident statistics, there will be about 1.3 accidents per million vehicle miles in 2020. The total accident frequency will be less than one per year in 1975, exceed one per month after 2000, and reach almost two per month in 2020.

In the overwhelming majority of cases, these accidents will not result in the release of radioactivity. On the average, only about 0.3 percent of the accidents in 2020 result in releases. The average release frequency ranges from approximately one release per 250 years in 1975 to one release per 13 years in 2020. The approximate average release rate ranges from one release per 100,000 shipments in 1975 to one release per 500,000 shipments in 2020.

The maximum average releases occur in 2020 when the transportation activity is the largest for the period under study. The average annual release of radioactivity from spent fuel is 13 curies of Kr-85, 0.031 curies of I-131 and 6.3 curies of mixed fission products. The average annual release from other materials transported in 2020 are: 0.017 curies from a plutonium shipment accident; 0.19 curies of fission products from high-level radioactive solid waste; and 11 curies from noble gas shipments. The expected values of the doses in 2020 to a hypothetical individual at a distance of 0.1 mile on the centerline downwind from an average ground level release from a transportation accident under average weather conditions are moderate. None of the average annual individual doses exceeds thresholds for biological effects.

The expected value of the annual population dose in 2020 is 6.4×10^{-4} person-rem whole body, 2.2×10^{-1} person-rem to the lungs, 1.8×10^{-2} person-rem to the GI tract and 1.9×10^{-1} person-rem to the thyroid. These population doses from transportation accidents of the nuclear power industry are very insignificant in comparison to the estimated annual population dose in 2020 from natural environmental sources of approximately 60 x 10^6 person-rem whole body.

The averaging process distributes the releases over all shipments. The actual release, when it occurs, will be larger than the average values. A typical actual release from an accident involving spent fuel would be about 1,000 curies of Kr-85, 1 curie of I-131, and 400 curies of mixed fission products. The release frequency would range from approximately one release per 250 years in 1975 to one release per 13 years in 2020. A typical actual release from a plutonium shipment accident would occur about once per 400 years in 2020 and release about 10 curies. A typical actual release from high-level solid radioactive waste would be about 2,000 curies with a frequency of occurrence in 2020 about once in 2,000 years. The smallest actual release from a noble gas shipment can be no less than the contents of one gas cylinder - about 180,000 curies of Kr-85. The frequency of occurrence is once in 14,000 years in 2020. None of the doses resulting from typical actual releases exceeds thresholds in biological effects in individuals at 0.1 mile.

For the worst-case releases considered, only lung doses exceed thresholds for fatalities and nonfatal effects for individual doses to the lung, GI tract, or thyroid. The highest lung exposure (1.6 Mrem) arises from plutonium with a frequency of occurrence in 2020 of about once in nine million years. An exposure of 9,900 rem to the lung could result from a high-level solid radioactive waste accident about once per seven million years in 2020. The lung exposure from spent fuel release could be 2,100 rem with a frequency of about once per 90,000 years. When both the probability of occurrence and the consequences are taken into account, the public health risks from worst-case releases of radioactivity from transportation accidents in the nuclear power industry to 2020 are small.

The public health risks from the transportation of radioactive materials in the nuclear power industry are so small that they do not warrant parametric assessment of the probability and consequences of accidents from facility site location, routing, mode, nor the identification of geographic regions of high risk. Based on the results of this study, additional regulation of transportation by routing, escort, speed control, or increased security of packaging does not appear to represent a significant improvement in controlling or limiting the overall risks from the nuclear power industry. The risks from transportation accident are not sufficient to provide a basis for the establishment of nuclear parks.

SECTION II

RECOMMENDATIONS

This study has shown that the public health risks from the release of radioactivity from transportation accidents in the nuclear power industry is relatively small. This result is due primarily to the low probability of accidents, the small fraction of the accidents resulting in release of radioactivity, and because the majority of releases are relatively small fractions of the radioactive contents. Nevertheless, when a release does occur, the amount of radioactivity released is sufficient to raise issues of public concern. Further effort is warranted to define an acceptable level of risk for activities whose consequences are highly statistical in nature.

The following recommendations are made to verify the low expected values of the consequences and to assure that uncertainties in some of the parameters would not alter the conclusions:

1. Accidents should be monitored to verify release probabilities and the relationships between accident severity and container damage.

2. Experiments should be performed to develop data for modeling energy transfer during accidents, i.e., the relationships between accident severity and container damage over a wide range of accident severities. The probability and severity of container damage should be used to evaluate the adequacy of regulatory standards for shipping containers.

3. Investigations should be conducted to verify the relationships between container damage severity and release fraction.

4. A data bank and associated data handling methodology should be implemented to accommodate distributional variations in the parameters used in this study. Among these parameters are nuclear power growth, facility locations, transportation scenarios, accident severity, container damage severity, release probability, release fractions, dispersion models, and population distribution.

SECTION III

STUDY PLAN

INTRODUCTION

The energy demands of the United States are increasing. Traditional energy sources are being depleted, and this fact means that there will be an increase in the fraction of energy supplied by nuclear fuel. By the year 2020, nuclear fuel is expected to provide as much as three-fourths of the electrical power of the United States. By that time, electrical power is expected to supply as much as one-third of the total energy requirements of the country.

The increased use of nuclear fuel will result in more mining, fuel enrichment, fuel fabrication, fuel reprocessing, and nuclear waste disposal. The facilities required to carry out these activities will not necessarily be located within the same area. It will be necessary, therefore, to transport nuclear fuels and wastes in a variety of forms and levels of radioactivity as it goes through the fuel cycle.

Associated with the transportation of these radioactive materials is a risk of the possible release of radioactivity during normal conditions of transport and from accidents. This radiological risk will increase with the growth in total transportation of nuclear fuels and radioactive materials of the nuclear power industry. The purpose of this study is to assess the risks from transportation accidents in the nuclear power industry to the year 2020.

EPA OBJECTIVES FOR THE STUDY

The responsibility for assessing and minimizing the detrimental environmental impact from many of man's activities rests with the U. S. Environmental Protection Agency (EPA). As a part of these responsibilities, EPA has undertaken the assessment of the total environmental impact resulting from the production of nuclear power. The transportation of nuclear materials may represent a significant fraction of the total impact resulting from the nuclear power industry. As the nuclear transportation industry grows, a larger burden of radioactivity may have to be borne by the public and the environment.

In the present study, the possible radiological releases as a result of transportation accidents and the consequences of such releases are analyzed. The purpose of the study is to assist the EPA in developing base information for use in establishing policies for the transportation of radioactive materials generated by the nuclear power industry. Additional objectives of the present study are to identify and evaluate important variables and to apply fault tree analysis to determine the frequency of releases of radioactive materials under varying accident conditions.

STUDY METHODOLOGY

The method used in this study is essentially a mapping mechanism. Figure 1 contains a diagram which illustrates the overall action of the mapping. The idea is to map a function, the amount of radioactive material being shipped, into a set of risks from accidents to the shipments involved. The amount of material being shipped is a function of several variables concerning the nuclear power and transportation industries.

In this study, risk is defined as the probability of an undesirable consequence times the magnitude or value of the consequence. Among these consequences are: release of radioactivity, population doses, fatalities, illnesses, etc. The total risk to the public is the expected value of the consequence under consideration. The expected value is the probability weighted sum of all values of the consequence.

The overall view described by Figure 1 is given in more detail in Figure 2. A series of calculations produced the final mapping. First, the amount of radioactive material being shipped is calculated from such variables as the number and power of nuclear generators, the capacity of chemical reprocessing plants, the number of metric tons of fuel burned and the isotopic composition of the residues. Second, the probability of accidents is calculated based on available accident statistics by transportation mode. Third, the probability of release from a given accident is calculated by means of fault tree analysis. Fourth, the environmental distribution of radioactivity released from accidents is calculated by means of a dispersion model. The results of this calculation are estimates of the dose to a hypothetical individual in an assumed scenario and the dose to the population. Finally, the lethal and nonfatal effects to humans are estimated from a health effects model.

The fault tree simulation model is based on the representation of the shipping container as a series of barriers that are breached with some computable probability. The use of a barrier model in a fault tree is a way to calculate the conditional probability that radioactive material is

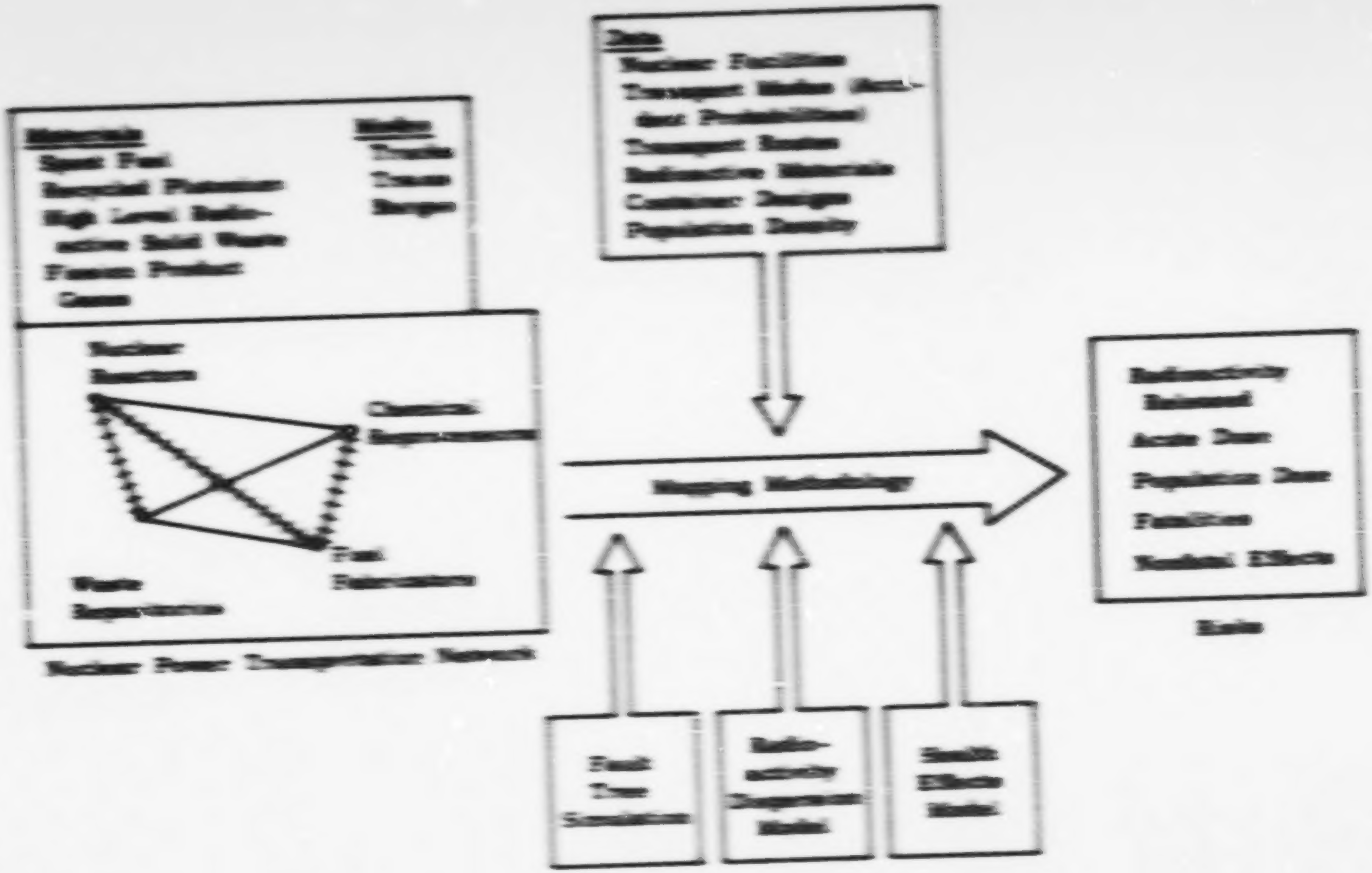

Materials
Spent Fuel
Recycled Plutonium
High Level Radioactive Solid Waste
Fission Product Gases
Modes
Trucks
Trains
Barges
Nuclear Reactors
Chemical Reprocessors
Fuel Fabricators
Waste Repositories
Nuclear Power Transportation Network
Data
Nuclear Facilities
Transport Modes (Accident Probabilities)
Transport Routes
Radioactive Materials
Container Designs
Population Density
Mapping Methodology
Fault Tree Simulation
Radioactivity Dispersion Model
Health Effects Model
Radioactivity Released
Acute Dose
Population Dose
Fatalities
Nonfatal Effects
Risks

FIGURE 1: OVERALL ORGANIZATION OF EVALUATION OF RISK FROM TRANSPORTATION ACCIDENTS IN THE NUCLEAR POWER INDUSTRY

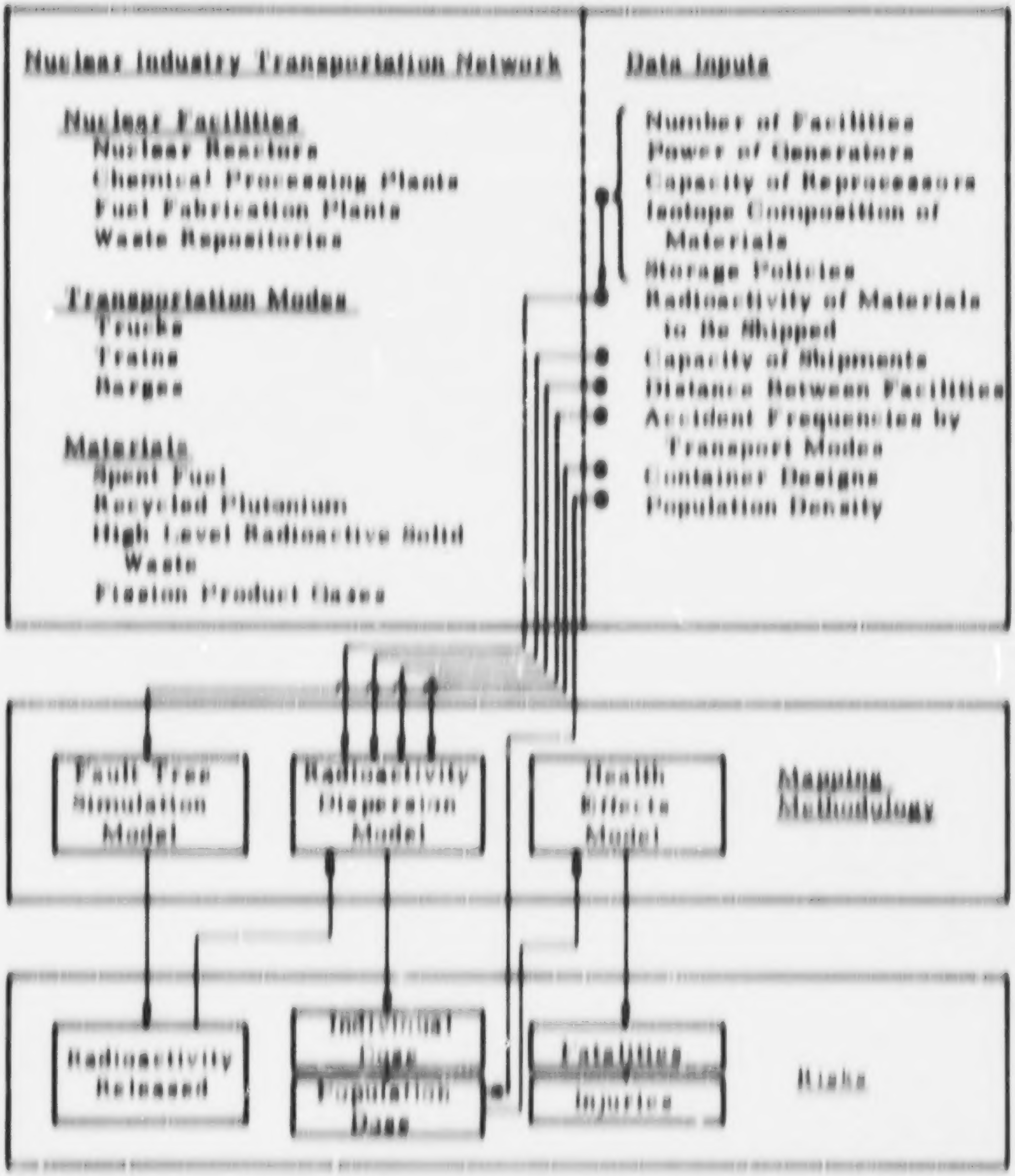

Nuclear Industry Transportation Network
Nuclear Facilities
Nuclear Reactors
Chemical Processing Plants
Fuel Fabrication Plants
Waste Repositories
Transportation Modes
Trucks
Trains
Barges
Materials
Spent Fuel
Recycled Plutonium
High Level Radioactive Solid Waste
Fission Product Gases
Data Inputs
Number of Facilities
Power of Generators
Capacity of Reprocessors
Isotope Composition of Materials
Storage Policies
Radioactivity of Materials to Be Shipped
Capacity of Shipments
Distance Between Facilities
Accident Frequencies by Transport Modes
Container Designs
Population Density
Fault Tree Simulation Model
Radioactivity Dispersion Model
Health Effects Model
Mapping Methodology
Radioactivity Released
Individual Dose
Population Dose
Fatalities
Injuries
Risks

FIGURE 2. DETAILED ORGANIZATION OF EVALUATION OF RISK FROM TRANSPORTATION ACCIDENTS IN THE NUCLEAR POWER INDUSTRY

released, given that an accident has occurred. These fault trees require input data in the form of conditional probabilities of elementary events. Examples of elementary events might be occurrence of puncture force greater than that which the barrier can withstand, or failure of a seal due to heat from a nearby fire. Such data are obtained from laboratory or field tests, distribution functions, statistical tabulations for similar events, and theoretical estimates. Once the fault tree has been completed and elementary probability data has been assigned, the release probability can be computed by Boolean algorithm or Monte Carlo simulation.

ELEMENTS INCLUDED IN THE STUDY

Nuclear facilities which produce or handle radioactive materials requiring transportation are confined in this study to the following:

1. Nuclear power reactors.
2. Chemical reprocessing plants.
3. Fuel fabrication plants.
4. Radioactive waste repositories.

The transportation modes which are considered in this study are:

1. Truck.
2. Rail.
3. Barge.

Operation of nuclear fuel cycles involves transportation of many materials. The following selected list of transported materials is chosen for study, since they are assumed to represent the highest potential risks under accident conditions:

1. Spent fuel.
2. Recycled plutonium.
3. High-level radioactive solidified waste.
4. Fission product gases.

Results of the analysis are presented as a set of risks:

1. The frequency of transportation accidents.
2. The radioactivity released from an accident.

3. The dose to a hypothetical individual exposed at an assumed distance from the point of release.
4. The population dose.
5. The number of fatalities expected from acute and latent effects.
6. The number of nonfatal effects.

In this study, annual risks are obtained for nuclear facility related transportation within the conterminous United States between 1975 and 2020. The set of risks is generated at five-year intervals, beginning in 1975. The fundamental parameters of the problem are listed as follows:

1. Capacities of shipments.
2. Number of shipments.
3. Average distance between facilities.
4. Transport mode mix.
5. Radionuclide composition of material cargo.
6. Physical form of material cargo.
7. Physical nature of accidents.
8. Accident severity.
9. Probability of loss of containment (release probability).
10. Fraction of radionuclide content of cargo released after loss of containment (release fraction).
11. Dispersion conditions in environment.
12. Biological response to specific radionuclides.
13. Population density distribution.
14. Fatal and nonfatal health effects.

In the present risk analysis of accidents, the principal parameters varied are population density, transport mode mix, material cargo, accident severity, and release fraction.

The severity of accidents is divided into minor, moderate, and severe categories. These classifications are functions of the relative velocity of colliding vehicles and of the time duration of fires associated with accidents. The release fraction is divided into small, medium and large categories.

ORGANIZATION OF STUDY

The potential risks associated with radioactivity released from nuclear transportation accidents in the nuclear power industry are identified and quantified in the following way: In Section IV, a reasonable picture of the United States nuclear industry from 1970 to 2020 is presented. This information is used in Section V to predict the amount and type of nuclear material transportation. The probabilities for the various types of accidents which can lead to release of radioactivity is calculated in Section VI. The release fraction, environmental dispersion, population dose and health effects models are described in Section VII. The evaluation of public health risks from transportation accidents to the year 2020 is summarized in Section VIII.

SECTION IV

THE UNITED STATES NUCLEAR INDUSTRY

INTRODUCTION

To evaluate the environmental impact of accidents occurring during transportation of nuclear material, it is necessary to know the numbers, origins, and destinations of the shipments; the types of vehicles and shipping containers used; and the expected population densities along the routes. These parameters are dependent on projections of the development of the nuclear industry and the population during the 50 years covered by this study.

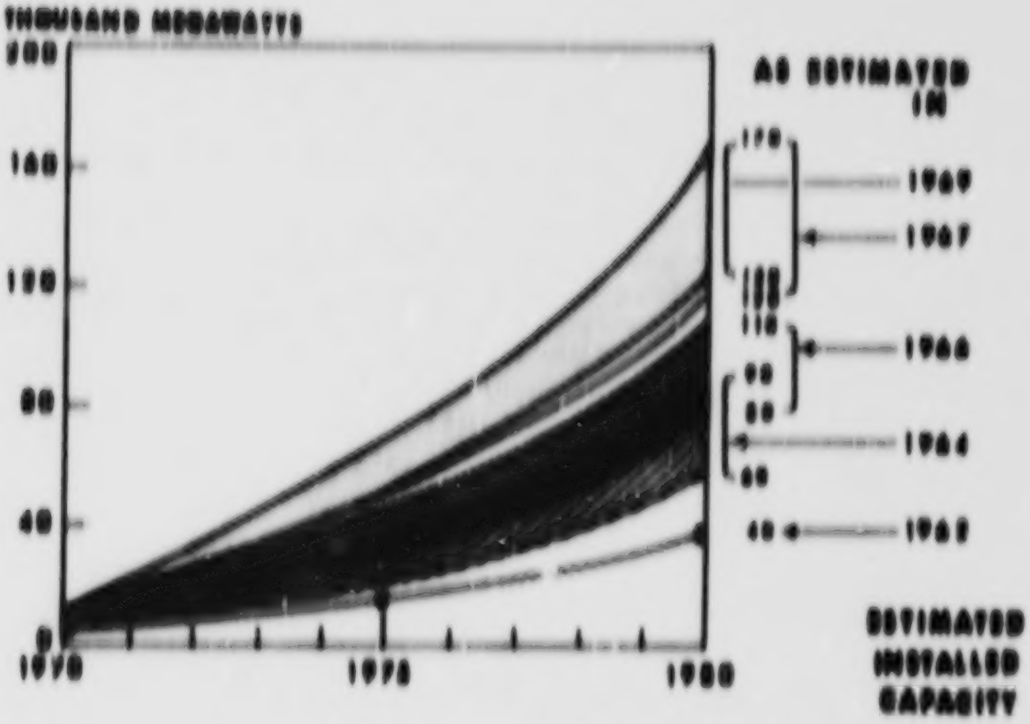
The aspects of the nuclear industry which are considered in a projection are:

1. The magnitude of the installed nuclear power capacity.
2. The relative contributions of each type of reactor to this capacity.
3. The long term disposal (or storage) policies for radioactive waste.
4. The economics of the fuel cycle.

Projections should be reevaluated periodically to make use of the most recent data. An example of an updated projection is given in Figure 3 (Reference 1). This figure shows the AEC's forecasts of the nuclear generating capacity in the decade 1970 to 1980. The first estimate was made in 1962. The forecast was revised in 1964, 1966, 1967, and 1969; each time it was revised upward. A more recent projection by the staff at Oak Ridge National Laboratory (Reference 2) indicates that the nuclear generating capacity in 1980 will more closely agree with the upper estimate made in 1966, 114 thousand megawatts.

In the 50-year period of this study, society may change its pattern of energy consumption. Technological breakthroughs may occur which will invalidate the underlying assumption of the projections. Nevertheless, since decisions must be made today, it is necessary to make predictions based on the best information and opinions available today.

The development of the United States nuclear industry over the next 50 years will be governed primarily by the demand for electrical energy. The energy crisis may result in a decrease in total electricity demand, but such a decrease is regarded as a fluctuation which does not influence the long term upward trend of demand. Military and scientific influences



Reference: "The Nuclear Industry - 1970," U. S. Atomic Energy Commission

FIGURE 1. PROJECTED NUCLEAR ELECTRIC CAPACITY

on the development of the nuclear industry are expected to be small compared to the influence of the domestic needs for more energy. In this section, the following aspects of the nuclear electric industry for the next 50 years are discussed:

1. Demand for electricity in the United States between 1970 and 2020.
2. Ways in which the electrical energy demand will be met.
3. Numbers, sizes, and types of facilities needed to support the nuclear energy requirements.

POPULATION GROWTH IN THE UNITED STATES

One of the major forces governing energy demand is the growth of the United States population. Table I shows the population of the conterminous United States in 1970 and the projected populations through the year 2020. This projection is based on an average of 2,775 children per 1,000 women at end of child bearing and a net annual immigration of 400,000. This birth rate is higher than that recently released by the Census Bureau. They report a rate of 2,080 children per 1,000 women (Reference 3).

The population of the United States is expected to increase significantly during the next 50 years. The population in 2020 is expected to be about 79 percent higher than in 1970. If the per capita energy demand were to remain constant, an increase of 79 percent in the overall energy demand would be expected by the year 2020.

The conterminous United States population density projections are also displayed in Table I. They are based on a constant land area of 3.04 million mi^2.

DEMAND FOR ELECTRICITY IN THE UNITED STATES

The standard of living and life style in the United States uses large amounts of energy for each person. It has been estimated that while having 6 percent of the world's 1970 population, the United States consumed one-third of the world's 1970 annual production of energy.

The demand for energy increases when the population increases or when the per capita demand for energy increases. Demand for electricity is only part of the total demand for energy, but it is the part for which nuclear reactors can provide an important supply.

TABLE 1. PROJECTED POPULATION OF THE CONTERMINOUS UNITED STATES

Year	Total[a] Population (10^6 Persons)	Average[b] Population Density (Persons/mi^2)
1970	204	67.1
1975	218	71.7
1980	233	76.6
1985	251	82.6
1990	269	88.6
1995	281	92.4
2000	298	98.0
2005	310	102.0
2010	327	107.6
2015	346	113.8
2020	365	120.0

[a] *Statistical Abstract of the United States, 1972*, U. S. Government Printing Office, July, 1972. Census Series C projections are used, based on a constant annual immigration rate of 400,000 and a constant fertility rate of 2,775 children per 1,000 women at end of child bearing.

[b] Based on constant land area of 3.04×10^6 mi^2.

The per capita demand for electricity was recently calculated from a projection of national demand (Reference 2). While the population is expected to increase by 1.8 over the next 50 years, the per capita demand for electricity is expected to increase 7.5 times from 21.5 kilowatt-hours per day (kwh/day) in 1970 to 160 kwh/day in 2020. Stated differently, each person used on the average about 0.327 megawatt-days (Mwd) of electricity during 1970, and would use about 2.4 Mwd in 2020. The total demand for electric energy in 1970 was 67 million Mwd compared with an estimated 888 million Mwd in 2020.

To illustrate the relations between electricity demand and population, the graphs of population, per capita demand, and total demand have been superimposed on the same figure in Figure 4.

NUCLEAR SUPPLY OF ELECTRICITY

The nuclear role in the electric economy will be played by both nuclear converter and breeder reactors. At the present time, the most important converter designs in the United States appear to be the light water reactors (LWRs), which include both the pressurized water reactors (PWRs) and the boiling water reactors (BWRs), and the high temperature gas cooled reactors (HTGRs). The most active development in the breeder field is currently the liquid metal cooled fast breeder reactor (LMFBR). Other breeder designs may account for appreciable contributions to the nuclear power picture within the next 50 years, but these will require further development.

A recent projection of installed nuclear generating capacity (presented in Table 3 and Figure 5) based on a study of economic competition between LWRs, HTGRs, LMFBRs, and fossil plants (Reference 4), was utilized for the analyses in this report.

TABLE 3. FORECAST OF NUCLEAR GENERATING CAPACITY

Year	Power Capacity (10^3 Mwe)			
	LWR	HTGR	LMFBR	Total
1970[a]	5			5
1975	45	0.3		45
1980	112	2		114
1985	210	35		245
1990	345	93	16	454
1995	476	151	113	740
2000	646	201	270	1,117
2005	933	273	756	1,962
2010[b]	520	350	1,140	2,010
2015	500	455	1,590	2,545
2020	490	590	1,960	3,040

[a] ORNL-TM-4224.
[b] Graphical extrapolation for years after 2005.

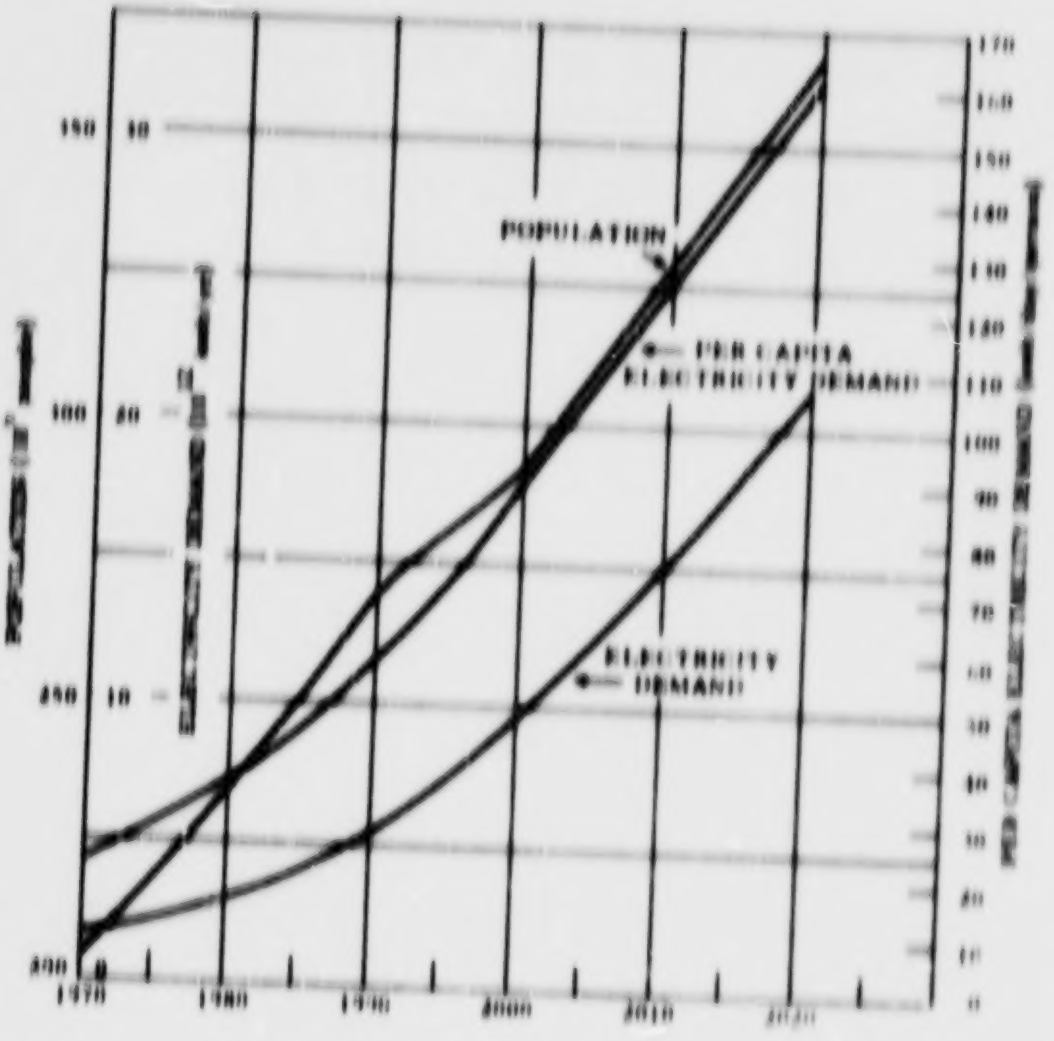


FIGURE 4. PROJECTED ELECTRICITY DEMAND

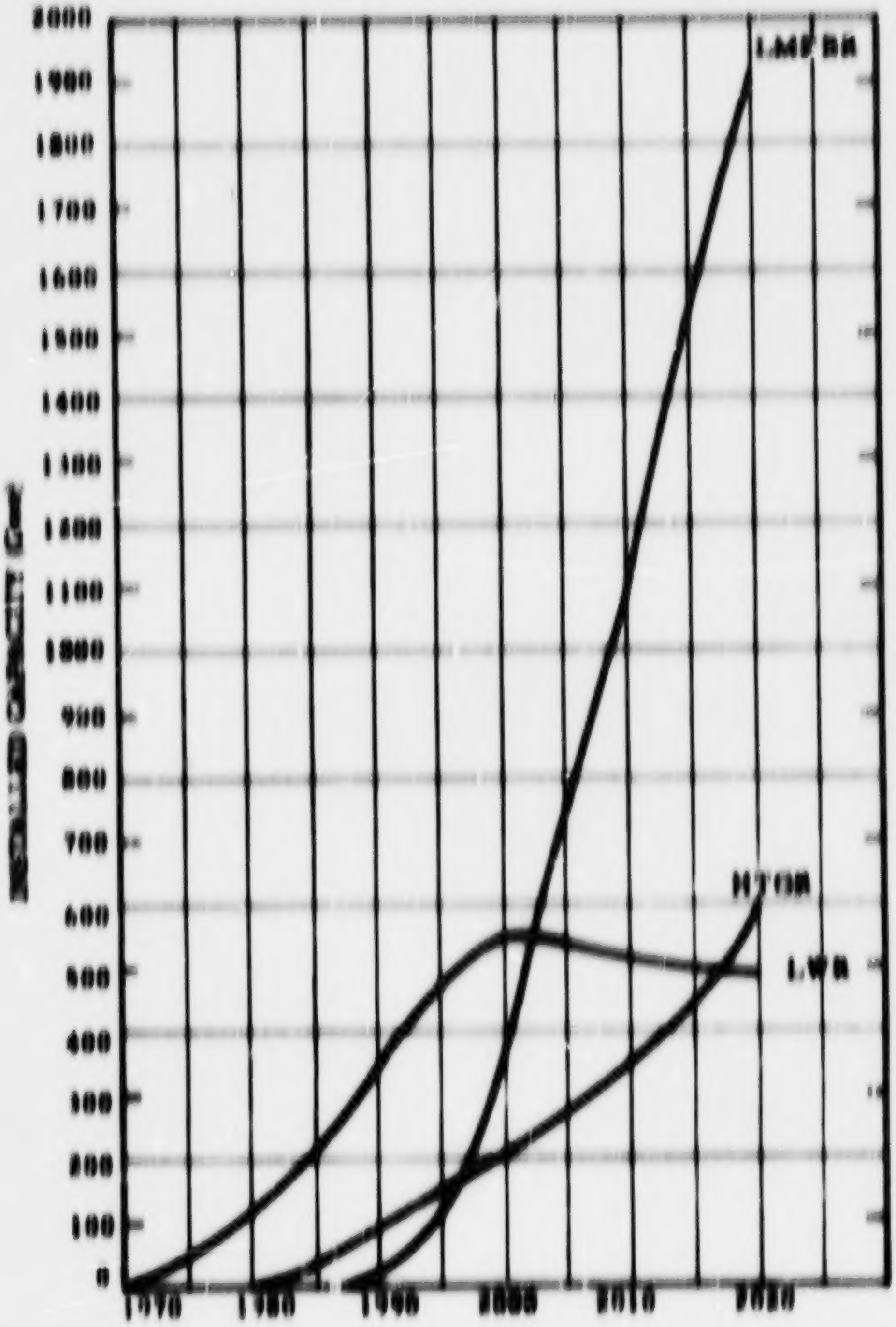


FIGURE 5. PROJECTION OF GENERATING CAPACITY OF VARIOUS NUCLEAR REACTOR TYPES

Earlier studies of optimum mixtures of generating plant designs have been published (References 5, 6). These forecasts differ only slightly from the one given above.

NUCLEAR FUEL CYCLES

To understand the transportation requirements of the nuclear power industry, the fuel cycles associated with the reactors producing the power must be understood. Transportation occurs between all plants in the nuclear fuel cycle since almost all the plants are geographically separated. In the future, construction of nuclear parks may obviate the necessity for transportation services for some materials, such as spent fuel and recycled plutonium, but the need for transporting wastes, uranium ore, thorium ore, and enriched fuel is not likely to be reduced.

Permanent waste repositories are in the development stage. One location in southeastern New Mexico is being examined as a possible site. A first coring sample of the salt bed information is expected to be taken in 1974 to allow a choice to be made between sites in New Mexico and Kansas. It is not anticipated that pilot plant operations will be started prior to 1985, while regular operation of the facility on a nonexperimental basis is not expected to take place before 1993. It is anticipated that if this project is successful and the salt formation disposal technique becomes publicly accepted, at least one other national disposal site will be in operation by the year 2000 (Reference 7). It is presently contemplated that all commercial high-level waste will be sent to a retrievable surface storage facility. Such facilities might be located at the AEC's facilities, such as Hanford, Oak Ridge, or Nevada. They are expected to be used primarily as holding facilities until such time as more permanent waste management methods are available.

Light Water Reactor

The fuel cycle of an LWR is schematically illustrated in Figure 6. The cycle begins with the mining of uranium ore. The uranium is separated from the ore by means of pulverizing, leaching, and calcining operations in a uranium mill. The mill's product is called yellowcake after its color and texture. The yellowcake consists of different oxides. Between 70 and 90 percent of the oxides contain uranium of varying stoichiometric composition, but they are collectively written as U_3O_8 (Reference 8). The uranium in the yellowcake consists of a mixture of isotopes. The composition of natural uranium is 99.28 weight percent U-238, 0.71 weight percent U-235 and a trace of U-234.

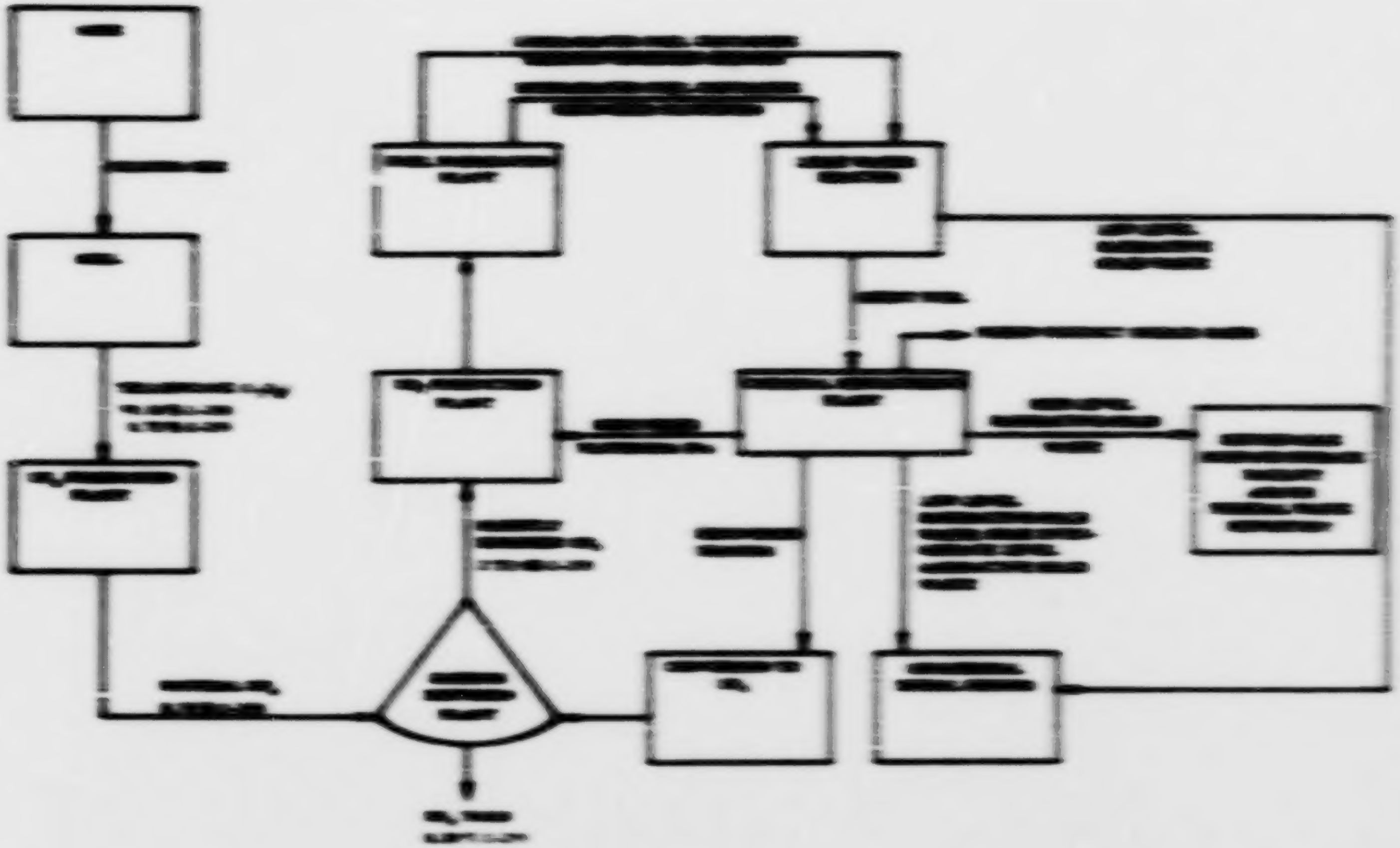


FIGURE 6. SCHEMATIC FUEL CYCLE DIAGRAM FOR LIGHT WATER REACTOR

Yellowcake is transported to a refining complex of plants for purification and conversion to uranium hexafluoride gas. The gas is then used as feedstock in a gaseous diffusion plant. The depleted tails product (~0.2 percent U-235) is stored for future uses, such as future breeder cycle fuel and as shielding material (Reference 9).

The enriched product (2 to 4 percent U-235) is transported to a fuel preparation plant where it is transformed to uranium dioxide. The dioxide powder is sintered and compressed into pellets. Rods of these pellets are then assembled to form fuel elements. Some fabrication plants combine the dioxide production and fuel element fabrication operations.

At operating equilibrium, LWRs are charged annually with about a fourth of a new core, which may utilize either U-235 or Pu-239 as the fissile isotope. In those LWRs utilizing recovered plutonium, only about a third of the new elements contain plutonium; the rest contain regular uranium fuel that is slightly enriched in U-235. The plutonium elements are mixtures of oxides of natural uranium and plutonium. Not all the plutonium consists of fissile isotopes, but the fissile isotopes Pu-239 and Pu-241 usually account for 70 to 90 percent of the plutonium mass.

When the reactor is shut down for refueling, some of the spent fuel is discharged. After a brief cooldown period to allow radioactive decay, say 150 days for LWRs without Pu recycle and 90 days for LWRs with Pu recycle, the spent fuel is shipped to a chemical reprocessing plant.

At the reprocessing plant, metal clad and metal end boxes are separated mechanically from the fuel. The fuel is dissolved in nitric acid followed by several chemical processes designed to separate radioactive fission products, uranium, plutonium, and other actinide elements.

The recovered uranium and plutonium are either recycled into new fuel or are stored. The uranium product is usually converted to uranium hexafluoride and shipped to the enrichment plant. The plutonium product is shipped as PuO_2 powder to a fuel preparation plant, where it is mixed with powder of natural UO_2. The mixture is then sintered into fuel pellets.

The aqueous waste solutions found at the end of the separation process contain some fission products and actinides and are classified by specific radioactivity levels into three categories (Reference 10):

High: >1 Ci/ℓ

Intermediate: 100 μCi/ℓ - 1 Ci/ℓ

Low: <100 μCi/ℓ

In two of the three known reprocessing plants, the waste liquid is stored in large tanks for up to five years to allow radioactive decay and then solidified. One of the plants produces a solid waste. The waste is stored in solid form until it is shipped to a permanent storage site. By regulation, all the waste must be shipped within ten years after it is generated in the separation processes.

The permanent storage site has not been selected at this time. Plans to construct a Retrievable Surface Storage Facility are being formulated until such time as a suitable site is found for the Federal Waste Repository.

The cladding and other fuel element hulls are contaminated with a small amount of fission products and actinides that have diffused from the fuel pin matrix into the cladding matrix during irradiation. While these materials present a radioactive hazard, they do not provide as large a heat removal problem as does high-level radioactive solid waste.

Calculations (Reference 6) of the composition of mass, radiation, and thermal power of irradiated Diablo Canyon PWR fuel assemblies yield insight into the distinction between high and intermediate levels of radioactive waste. After the fuel has decayed 150 days after discharge from the reactor, the fission products and actinide elements in high-level waste and activation products in the intermediate waste (assumed to be the Zircaloy-4 cladding and Inconel spacers taken from the assemblies) may be compared as follows:

Waste	Mass (MT)	Radiation (MCi)	Thermal Power (kw)
Fission Products in High-Level Waste	0.035	4.390	19.300
Actinide Elements in High-Level Waste	0.006	0.018	0.646
Activation Products in Intermediate-Level Waste (Cladding)	0.271	0.028	0.224

From this comparison, the solid wastes may be classified qualitatively on the basis of radioactivity and heat removal as shown on the following page (Reference 11).

Level	Radioactivity Containment Problem	Heat Removal Problem
High	Substantial	Substantial
Intermediate	Significant	Not serious
Low	Not serious	Not serious

The methods for disposal of intermediate level waste have not been fully resolved. Currently, it is lumped together with low level waste and transported from the chemical processing plants to commercial burial grounds for permanent disposal in the earth. However, future quantities of intermediate level waste may be disposed at the Federal Waste Repository, along with high-level waste.

Low level waste includes not only the solid made from the liquid waste of little radioactivity, but also sludges, resins, contaminated equipment, clothing, packaging, and sundry items. All this material is transported to commercial burial grounds for disposal.

In the course of processing, some of the fission products, isotopes of iodine, xenon, and krypton, evolve as off-gases. Current practice is to vent these gases to the atmosphere, where they are diluted to very small concentrations. Future production levels of these gases may become great enough to warrant the collection of these gases. Presumably, the collected gas will be bottled and shipped to the Federal Waste Repository for storage along with other fission products. As yet, no rules for these actions have been formulated.

LWR Without Pu Recycle - A quantitative example of the material flows in an LWR fuel cycle with no plutonium recycle is presented in Figure 7. The annual flow rates are based on the Diablo Canyon PWR design. Wastes from a BWR are expected to be comparable.

The amount of waste that must be transported from the chemical reprocessing plant to the Federal Waste Repository is a function of the specific power and burnup characteristics of the reactor. The fuel cycle pictured in Figure 7 is based on a specific power of 37.5 Mw_t/MTU with an 80 percent load factor.

LWR With Pu Recycle - Recovery of plutonium generated in the irradiation part of one LWR fuel cycle for use as fissile fuel in another cycle is economically advantageous. With Pu recycle, about a third of the fuel

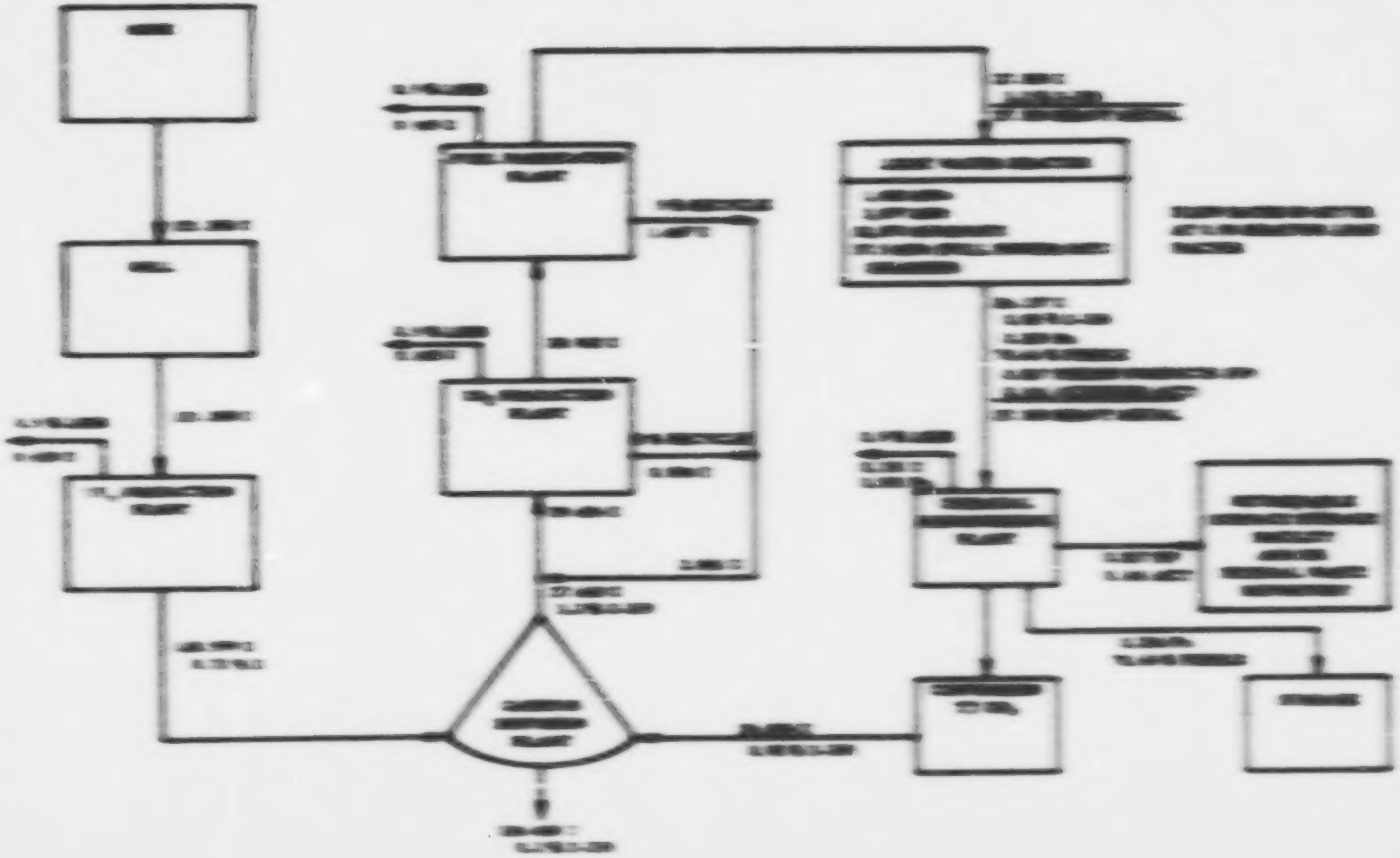


FIGURE 7. MATERIAL FLOW IN TYPICAL LWR FUEL CYCLE WITHOUT PLUTONIUM RECYCLE. (SOURCE: TABLE 2, ORNL-TM-[illegible].)

elements in the annual charge to the reactor contain plutonium. Using the steady state replacement of 1.21 atoms fissile plutonium for each atom U-235 in 32.4 percent of the fuel elements (Reference 8), the quantitative fuel cycle shown in Figure 8 results. The quantities of fission products and actinides are based on an 80 percent load factor and a specific power of 37.5 $MW_t/MT(U+Pu)$.

High Temperature Gas Cooled Reactor

The fuel cycle of the HTGR is similar to the LWR fuel cycle, except that the fissile material is nearly fully enriched U-235 and the fertile material is primarily thorium. Thus, there is the additional requirement for the mining and shipment of thorium. A quantitative graphical representation of the HTGR fuel cycle is given in Figure 9 (Reference 8).

More efficient fuel utilization in operation of the HTGR is possible if the fissile material is U-233 instead of U-235 (Reference 12). However, the U-233 will not be available until produced in HTGRs or breeder reactors using thorium. One breeder well suited for this purpose is the Gas Cooled Fast Reactor (GCFR) using modifications of HTGR technology. Since it is not as well developed as the LMFBR, use of the GCFR in the nuclear economy has not been anticipated in this forecast.

The fuel in the HTGR consists of particles of uranium or thorium coated with layers of pyrolytic carbon. The coatings contain the fission products as they form during irradiation. Such a ceramic fuel leads to a different set of techniques for separation of recoverable fuel and fission products than those used for LWR oxide fuel. The HTGR fuel is crushed and burned to free the fuel from the graphite. The U-235 recycle particles are separated by mechanical screening. Chemical processes are then applied to the other fuel particles to separate the fission products and actinides in the fuel.

Liquid Metal Cooled Fast Breeder Reactor

A quantitative representation of the fuel cycle for LMFBR is illustrated in Figure 10. The annual flow rates are based on the Atomics International Follow-on Design (Reference 8). The reactor is composed of two regions: a core containing fissile nuclei and a blanket containing fertile nuclei. The core fuel elements contain about 15 weight percent fissile isotopes of plutonium. The blanket utilizes depleted uranium tails left from the enrichment process.

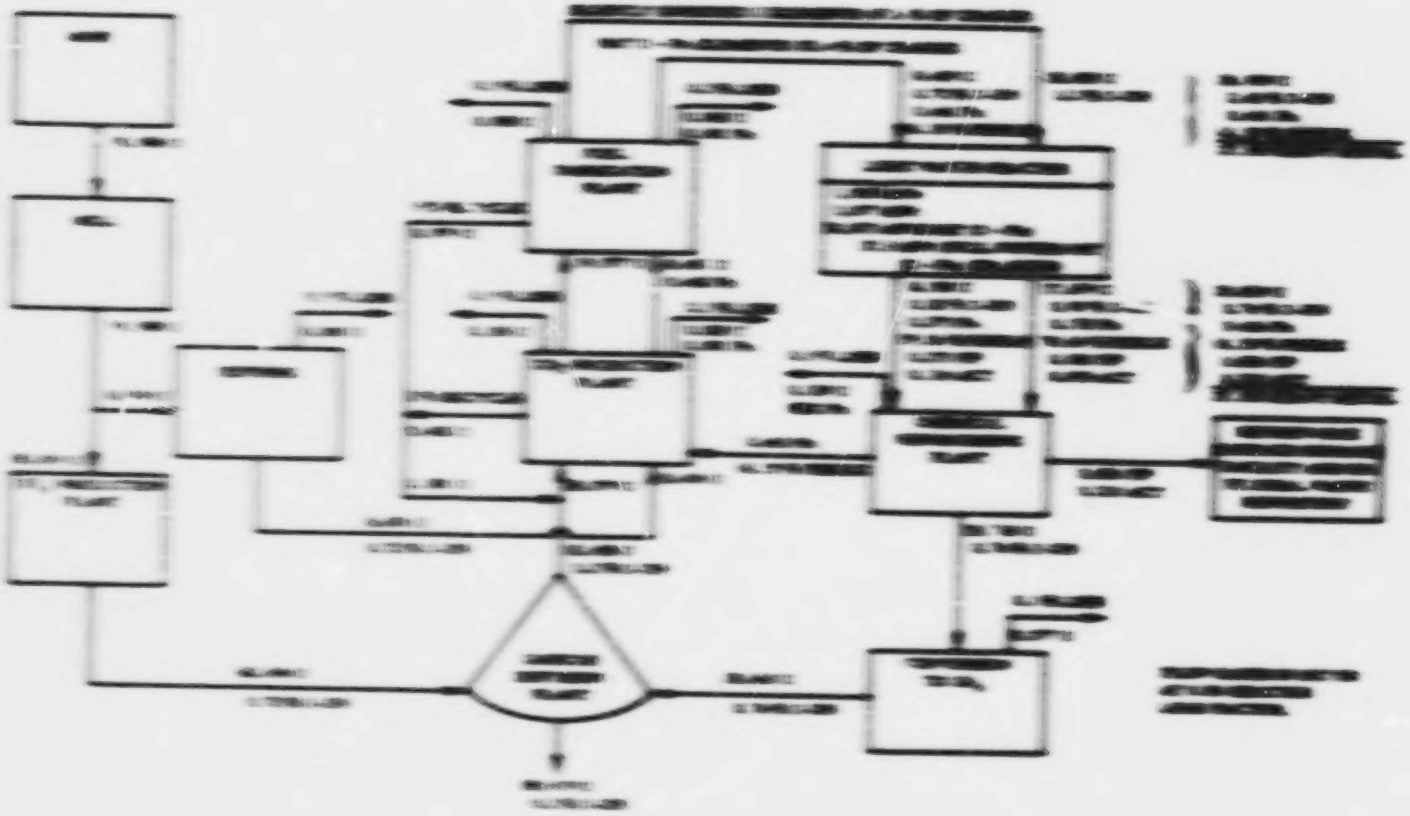


FIGURE 6. MATERIAL FLOW IN TYPICAL LWR FUEL CYCLE WITH PLUTONIUM RECYCLE. (SOURCE: TABLE 2, [illegible].)

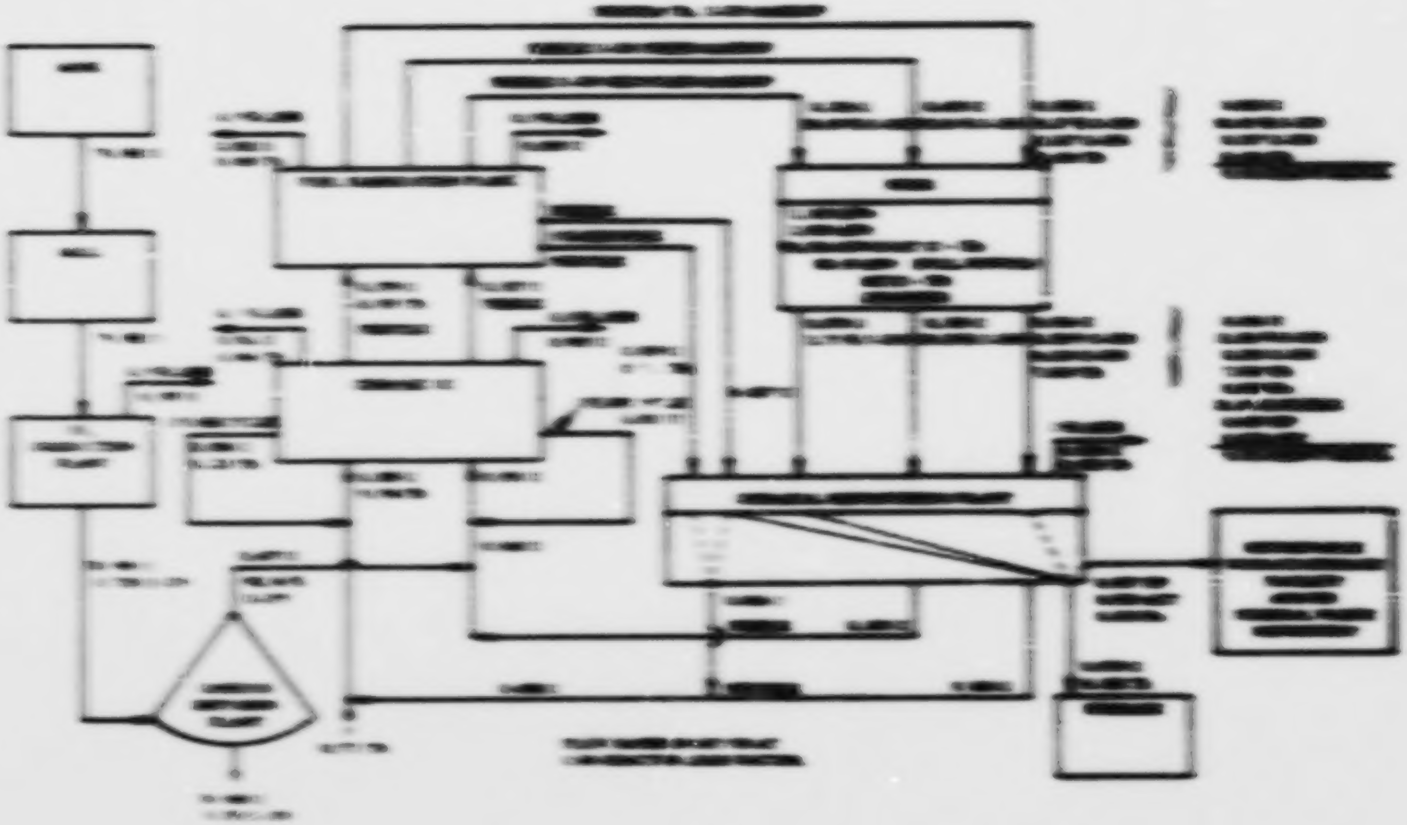


FIGURE 4. MATERIAL FLOW IN TYPICAL HTGR FUEL CYCLE.
(SOURCE: TABLE 1, ERDA-76-43.)

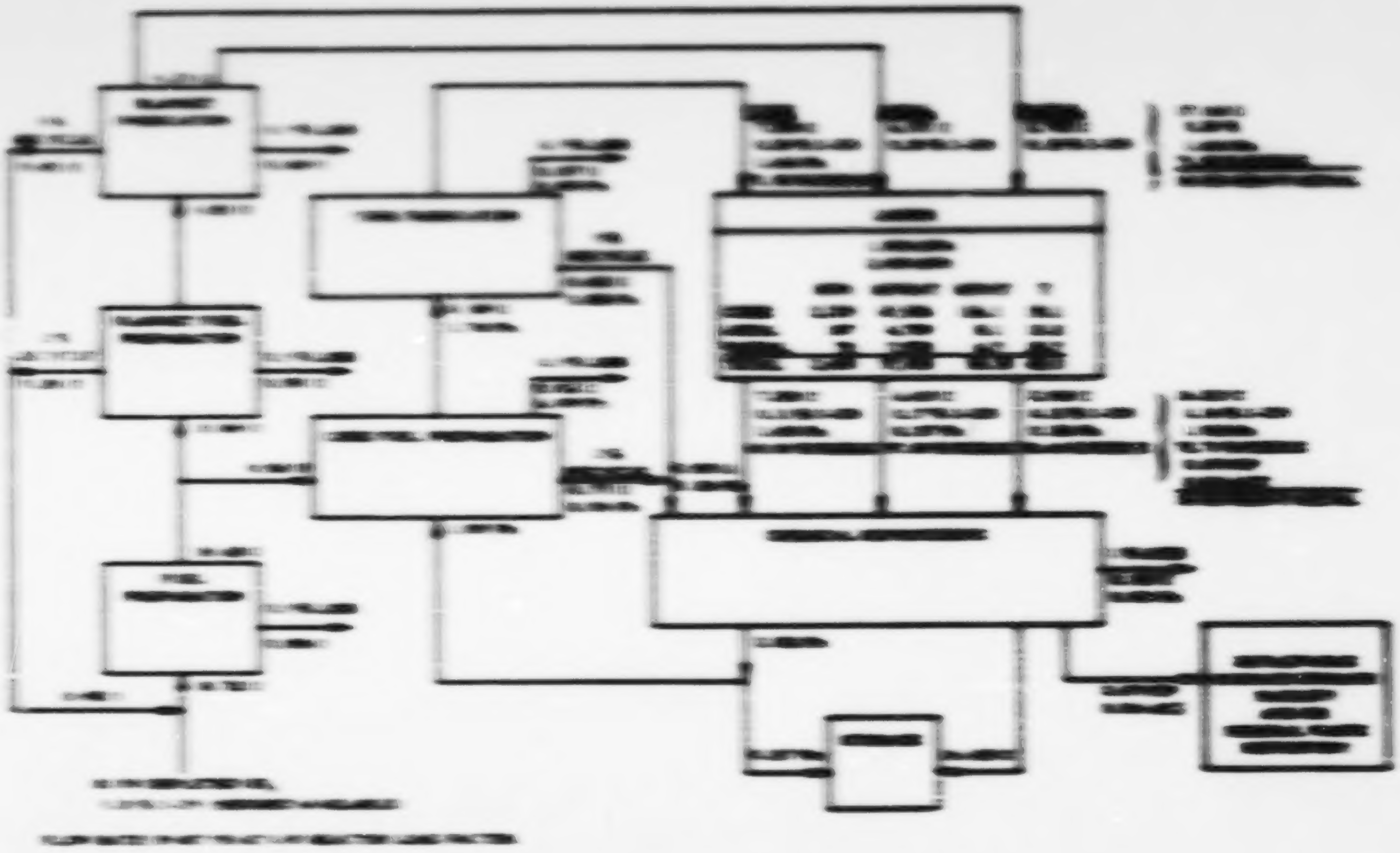


FIGURE 11. MATERIAL FLOW IN TYPICAL LMFBR FUEL CYCLE
(SOURCE: TABLE 1, [illegible])

The transportation services required in the LMFBR fuel cycle include shipping depleted UF$_6$ from enrichment plant to the fuel preparation plant as well as recycling uranium and plutonium recovered from fuel preparation and fuel fabrication plants. The uranium from chemical processing plants is shipped to waste storage.

Separation techniques for LMFBR fuel are still being developed. The process is similar to that for LWR fuel in that the fuel elements are mechanically disassembled. Volatile fission products are then removed by heating. The oxide fuel is then separated from the stainless steel cladding by dissolution in nitric acid. Chemical separation processes are then employed to separate the plutonium fuel from the fission products, other actinides, and alpha-contaminated wastes.

SECTION V

NUCLEAR TRANSPORTATION FORECASTS (1975 to 2020)

ANNUAL FUEL REQUIREMENTS

The nuclear power economy forecast in Table 2 involves large requirements in fuel fabrication from plutonium produced in nuclear reactors and from uranium and thorium mined from the earth. In 1979, some LWRs are supposed to begin using recycled plutonium in their fuel elements. Consequently, fabrication of these elements is scheduled for 1978. Introduction of LMFBRs is forecast for 1987. Recycle of plutonium in LWR fuel is presumed to stop then. Use of LMFBRs is expected to increase rapidly after 1990; half or more of all fuel fabricated after 2005 will be LMFBR fuel. Use of LWRs is anticipated to increase until year 2000 and then to decrease at a slow rate. Some of the plutonium bred in the LWRs will be used in LWRs, but most of it will sustain the LMFBRs. The commercial operation of HTGRs is expected to flourish by 1980 and continually increase through the balance of the 50-year period.

The forecast for the amounts of these fuels that will be used annually in the fabrication of fuel is given in Table 3 and Figure 11. The total amount of fuel fabricated is expected to double every 5 years until about 1985.

The LWRs using plutonium recycle are charged with two types of fuel: one in which the fuel pins contain natural uranium and plutonium and one in which the fuel pins contain slightly enriched uranium only. In reactors irradiating recycled plutonium, only about one-third of the fuel elements actually contain plutonium. The plutonium constitutes about 3 weight percent of these fuel elements.

ANNUAL SPENT FUEL TRANSPORTATION

The estimated annual discharge of spent fuel from power reactors for the next 50 years is presented in Table 4 and Figure 12. These numbers were calculated under the assumption of an 80 percent load factor. They provide the annual quantities of spent fuel that must be transported from the reactors to the processing plants with cooling times taken into account. Values for the cooling times and burnup values have been assumed as follows:

Reactor Type	Cooling Time (days)	Burnup (Gw(t)d/MT)
LWR	150	33
HTGR	165	94
LMFBR	90	37

TABLE 1. ANNUAL PRODUCTION OF IRRADIATED FUEL.

	[illegible]										
	LWR				HTGR			LMFBR			
	No Plutonium Recycle-Slightly Enriched Uranium	Plutonium Recycle									
Year		Natural Uranium	Plutonium	Subtotal	Uranium	Thorium	Subtotal	Uranium	Plutonium	Subtotal	Total
1975	1.57			1.57							1.57
1980	[illegible]	0.72	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]				[illegible]
1985	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]				[illegible]
1990	[illegible]			[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
1995	[illegible]			[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
2000	[illegible]			[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
2005	[illegible]			[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
2010	[illegible]			[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
2015	[illegible]			[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
2020	[illegible]			[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

[a] [illegible]

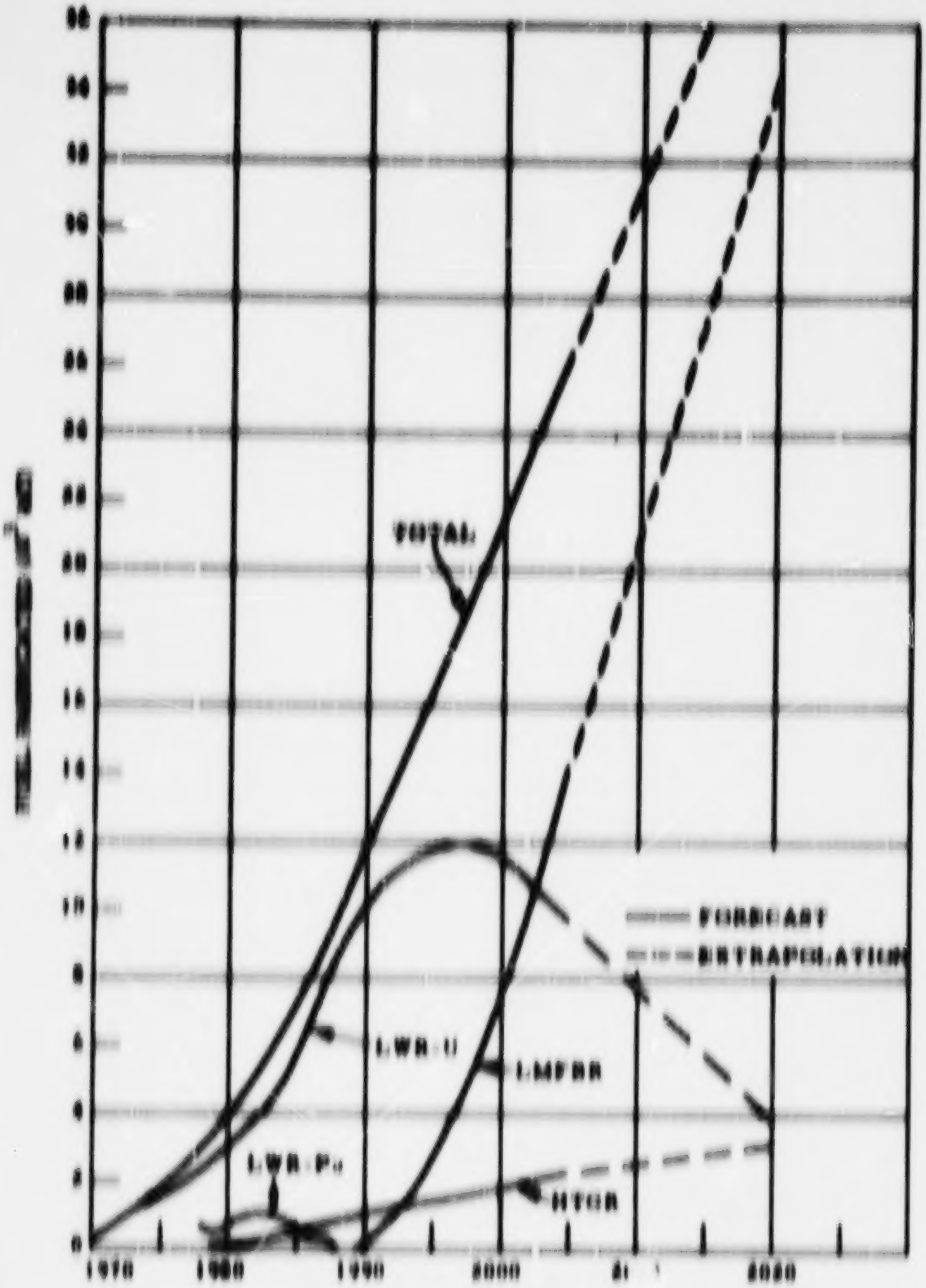


FIGURE 11. PROJECTION OF ANNUAL NUCLEAR FUEL FABRICATION REQUIREMENTS

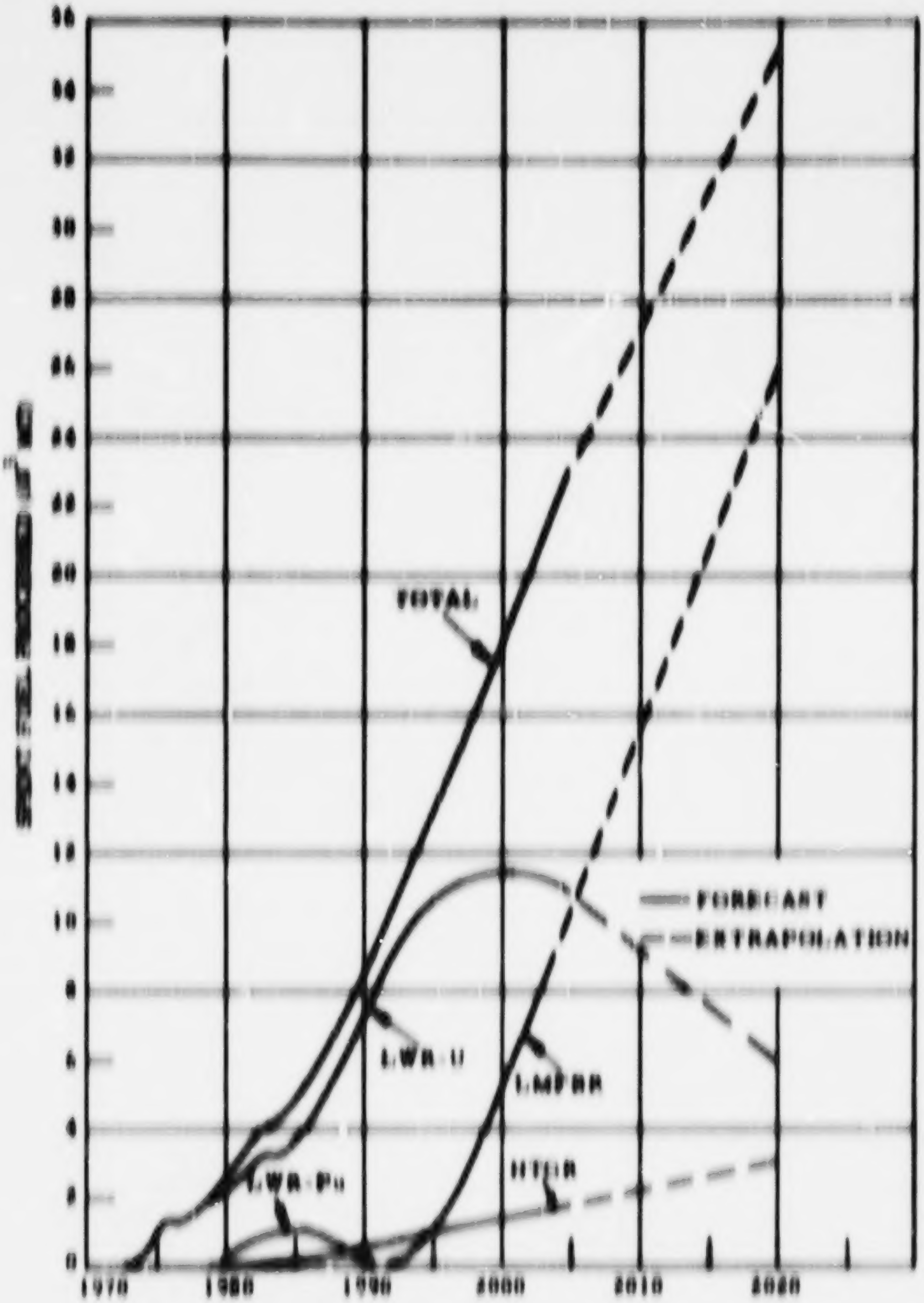


FIGURE 12. PROJECTION OF ANNUAL NUCLEAR FUEL REPROCESSING REQUIREMENTS

TABLE 4. ANNUAL DISCHARGE OF SPENT FUEL AFTER COOLING

Amount of Spent Fuel (10^3 MT Heavy Metal)[a]						
	LWR					
Year	LWR Without Plutonium Recycle	LWR With Plutonium Recycle	Subtotal	HTGR	LMFBR	Total
1975	0.05		0.05			0.05
1980	2.12	0.27	2.39	0.01		2.40
1985	3.57	1.18	4.75	0.17		4.92
1990	7.28	0.37	7.65	0.59	0.18	8.42
1995	10.48		10.48	1.04	1.47	12.99
2000	11.04		11.04	1.42	5.13	17.59
2005	10.64		10.64	1.81	10.68	23.13
2010	9.30		9.30	2.20	15.60	27.10
2015	7.80		7.80	2.60	20.50	30.90
2020	6.00		6.00	3.00	25.40	34.40

[a] ORNL-TM-4224. Data for 2010-2020 are extrapolations.

The spent fuel contains varying amounts of uranium, plutonium, other actinides, fission products, and thorium, depending on the type of reactor. The assays of the different types of fuel at time of processing are derived from data in Figures 7 to 10 and are collected in Table 5.

The radioactivities of major fission product nuclides, actinide nuclides, and activation product nuclides present in the spent fuel of each reactor type at the time of processing are listed in Table 6. Also shown in Table 6, is the radioactivity in waste after 10 years of storage. The totals were applied to the data in Table 4 to obtain the amounts of radioactivity transported each year in spent fuel shipments. The results of this calculation are posted in Table 7.

TABLE 5. ASSAY OF NUCLEAR FUELS AT TIME OF REPROCESSING

Fuel Component	Weight Percent in Different Fuels			
	LWR			
	Not Containing Recycled Pu	Containing Recycled Pu	HTGR	LMFBR
Uranium	95.54	92.56	7.99	86.12
U-235	0.82	0.52	11.86	0.34
U-233	-	-	28.82	-
U-238	99.18	99.48	59.32	99.66
	100.00	100.00	100.00	100.00
Plutonium	0.95	3.00	0.10	10.15
Fissile	71.44	53.62	-	72.73
Nonfissile	28.56	46.38	-	27.27
	100.00	100.00	-	100.00
Thorium	-	-	82.17	-
Fission products	2.99	3.06	9.53	3.48
Actinides other than U or Pu	0.52	1.38	0.21	0.25
TOTAL	100.00	100.00	100.00	100.00

TABLE 6. TYPICAL RADIOACTIVITY IN FUEL AND WASTES AT FUEL REPROCESSING PLANTS[a]

Nuclide	Concentration (Curies/MT Heavy Metal Charged to Reactor)							
	LWR-U		LWR-Pu		HTGR		LMFBR	
	Fuel	Waste	Fuel	Waste	Fuel	Waste[b]	Fuel	Waste
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

TABLE 6. (Continued)

Nuclide	Concentration (Curies/MT Heavy Metal Charged to Reactor)							
	LWR-U		LWR-Pu		HTGR		LMFBR	
	Fuel	Waste	Fuel	Waste	Fuel	Waste	Fuel	Waste
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
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[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
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[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
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[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
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[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
TOTAL	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

[a] Based on calculations in ORNL-TM-[illegible] and ORNL-TM-[illegible]. Fuel at time of reprocessing. Waste after 10 years storage.

TABLE 7. RADIOACTIVITY OF ANNUALLY TRANSPORTED SPENT FUEL

Year	Radioactivity of Spent Fuel (10^3 MCi)					
	LWR Without Pu Recycle	LWR With Pu Recycle	Subtotal	HTGR	LMFBR	Total
1975	3.82		3.82			3.82
1980	9.54	1.48	11.02	0.05		11.07
1985	16.06	6.49	22.55	0.78		23.33
1990	32.76	2.04	34.80	2.71	1.82	37.51
1995	47.16		47.16	4.78	14.86	61.94
2000	49.68		49.68	6.53	51.81	56.21
2005	47.88		47.88	8.33	107.87	164.08
2010	41.85		41.85	10.12	157.56	209.53
2015	33.75		33.75	11.96	210.08	255.79
2020	27.00		27.00	13.80	264.62	305.42

Spent fuel may be transported in various sizes of shipment. The several states impose restrictions on weights of shipments made by motor freight. The legal weight limit in most states is about 33 MT (73,000 lb) gross vehicle weight. Such a shipment can accommodate a spent fuel shipping cask that weighs about 22 MT (48,000 lb) when unloaded and contains 0.5 MTU equivalent of spent fuel. Special permits are issued in some states to admit truck shipments of heavier gross vehicle weights up to 71 MT (156,500 lb), although most states issuing such permits post a 50-MT (110,000 lb) limit (Reference 13). A compendium of information on possible spent fuel shipment sizes is included in Table 8.

The most popular mode will probably be rail shipments utilizing the GE IF 300 cask since it is the largest of the currently licensed containers. This cask may hold 7 PWR elements or 18 BWR elements, or equivalently a spent fuel mass of 3.15 MTU. A larger cask is being designed that will

TABLE [illegible]. SPENT FUEL SHIPMENT CAPACITIES

Designation	Mode	Cask Data
[illegible]^a [illegible]	Truck, rail, or barge	Cask: [illegible] m dia x [illegible] m long Cavity: [illegible] m dia x [illegible] m long Shield: [illegible] Contents: [illegible] MTU Number of elements: [illegible] BWR or [illegible] PWR Tare weight: [illegible] Number of casks per shipment: 1
[illegible]^b	Intermodal: overweight truck - rail or barge	Cask: [illegible] m dia x [illegible] m long Cavity: [illegible] m dia x [illegible] m long Shield: depleted uranium, stainless steel, water Contents: [illegible] MTU Number of elements: [illegible] BWR or [illegible] PWR Number of casks per shipment: 1
[illegible]^b	Rail or barge	Cask: under development Contents: more than [illegible] MTU Number of elements: [illegible] BWR or [illegible] PWR Number of casks per shipment: 1
[illegible]^b [illegible]	Rail	Cask: [illegible] m dia x [illegible] m long Cavity: [illegible] m dia x [illegible] m long Shield: [illegible] m Pb Weight: [illegible] MT loaded, [illegible] MT empty Number of casks per shipment: 1

[a] Directory of Shipping Containers for Radioactive Materials. United States Atomic Energy Commission. Washington, D. C. [illegible]

[b] Transportation of Nuclear Fuel. Report to Southern Interstate Nuclear Board. Atlanta, Georgia. December [illegible]

hold 15 PWR elements or 32 BWR elements, or equivalently a spent fuel mass of 6.75 MTU.

Smaller shipments by truck will still be used to serve those reactors without access to rail transportation and those reactors close to the chemical processing plants. Two truck shipment sizes are considered here: a legal weight shipment of 0.45 MTU capacity and an overweight shipment of 0.90 MTU capacity.

Some shipments by barge are anticipated. These shipments will involve a modal interchange since not all reactors or chemical processing plants will have access to water transportation. If barge shipments are made, they will probably be used only in conventional shipping lanes such as the Atlantic and Pacific seacoasts, the large river systems (e.g., Mississippi, Missouri, Ohio, and Hudson), and the Great Lakes.

The transportation scenario for spent fuel adopted for this study is shown in Table 9. Using this scenario, the annual number of spent fuel shipments was calculated from the data in Table 4. The results are shown in Table 12.

TABLE 9. SPENT FUEL TRANSPORTATION SCENARIO

Mode	Use (Percent)	Capacity (MTU Equivalent)
Legal Weight Truck	5	0.45
Overweight Truck	5	0.90
Small Cask on Rail	70	3.15
Large Cask on Rail	15	6.75
Barge and Overweight Truck	5	3.15
AVERAGE	100	2.34

Data on the distances between nuclear power reactors operating in 1970 and the three known sites of chemical processing plants are presented for truck and rail transport modes in Table 10. The distance over which spent fuel shipments must travel varies strongly with the location of the

TABLE 10. DISTANCES BETWEEN NUCLEAR POWER REACTORS OPERATING IN 1970 AND KNOWN CHEMICAL PROCESS PLANT SITES

	Chemical Processing Plant Sites					
	West Valley, New York		Barnwell, South Carolina		Morris, Illinois	
Reactor Site	Distance by Truck (mi)[a]	Distance by Rail (mi)[b]	Distance by Truck (mi)[a]	Distance by Rail (mi)[b]	Distance by Truck (mi)[a]	Distance by Rail (mi)[b]
Shippingport, Pennsylvania	217	217	593	696	501	519
Buchanan, New York	450	433	952	918	923	979
Rowe, Massachusetts	322	426	1,090	1,082	885	1,018
Haddam Neck, Connecticut	450	480	962	962	953	1,100
Toms River, New Jersey	408	404	658	751	862	988
Scriba, New York	125	154	1,064	1,127	729	787
Waterford, Connecticut	450	575	962	987	953	1,031
Peach Bottom, Pennsylvania	365	346	601	697	762	770
Big Rock Point, Michigan	640	647	1,080	1,121	459	452
Lagoona Beach, Michigan	354	365	758	846	315	292
Hartsville, South Carolina	653	948	113	117	1,038	989
Two Creeks, Wisconsin	748	864	1,129	1,129	259	294
Morris, Illinois	570	648	908	978	0	0
Genoa, Wisconsin	638	678	1,193	1,286	323	308
San Clemente, California	2,646	2,758	2,452	2,559	2,095	2,077
Humboldt Bay, California	2,862	3,188	3,018	3,282	2,429	2,476
Richland, Washington	2,477	2,569	2,852	2,911	1,874	2,046
AVERAGE	868	927	1,209	1,251	901	976

[a] Rand McNally Road Atlas: United States, Canada, and Mexico, 43rd Annual Edition, Rand McNally & Company (1967).

[b] Rand McNally Handy Railroad Atlas of the United States, Rand McNally & Company (1971).

reactors. If a shipment of spent fuel from any of these reactors were to be randomly sent to either of the processing plants, it must traverse an average distance of 991 miles by truck or 1017 miles by rail.

If additional chemical processing plants were built in the vicinities of Salt Lake City, Utah; Dallas, Texas; Cincinnati, Ohio; and St. Paul, Minnesota, and nuclear power plants were constructed fairly uniformly throughout the country, the average spent fuel shipment distance would decrease from the 1970 value of about 1000 miles to about 400 miles. The future behavior of this parameter is uncertain. It may stay rather constant if future reactor construction is centered around a few processing plants, or it may decrease nearly to zero if the construction of nuclear parks becomes the vogue. For purposes of this study, the average shipment distance is assumed to decrease linearly from 1000 miles at the start of 1970 to 400 miles at the end of 2020. The distinction between truck and rail distances is negligible for 1970 and no distinction between these modes for the future is anticipated.

To ascertain a value for the shipment distance by barge transport, the average is taken of such voyages as those from northeast ports or Florida ports to Steel Landing near the Barnwell, South Carolina, chemical processing plant down the Atlantic seaboard, applicable Great Lakes routes, applicable Mississippi and Ohio River routes, and possible shipments from the Southern California or Puget Sound areas to San Francisco port. These data are listed in Table 11. This distance parameter is assumed to remain constant at 565 miles over the fifty year period under investigation, since the location of the ports that will be used for modal interchanges between truck and barge or rail and barge is expected to be insensitive to the location of reactors.

The average shipment distance with respect to all modes is obtained by means of the modal use spectrum postulated in Table 9 is shown in Table 12.

By way of summary, the annual shipping data for spent fuel are collected in Table 12. The annual shipping units, which are measured in units of a million shipment-miles, grow until 2005, increasing about one million shipment-miles every five years. After 2005, the annual shipping units remains essentially constant at about 6 million shipment-miles per year.

ANNUAL PLUTONIUM TRANSPORTATION

The annual amounts of plutonium appearing in the chemical reprocessing plants was calculated by combining the data in Table 4 with the Pu data from Table 5. The results are tabulated in Table 13.

TABLE 11. DISTANCES BETWEEN SEA PORTS FOR SPENT FUEL SHIPMENTS

Origin Port	Destination Port	Distance (Mi)[a]
New York Harbor, New York	Steel Landing, South Carolina	890
Miami, Florida	Steel Landing, South Carolina	660
Portland, Maine	Philadelphia, Pennsylvania	550
Cleveland, Ohio	Buffalo, New York	180
Green Bay, Wisconsin	Chicago, Illinois	255
New Orleans, Louisiana	Cincinnati, Ohio	1,000
St. Louis, Missouri	St. Paul, Minnesota	575
Los Angeles, California	San Francisco, California	370
Seattle, Washington	San Francisco, California	810
AVERAGE		585

[a] Barge distance data computed from map of United States of America, Federal Aid Highways, U. S. Department of Transportation, Washington, D. C. (1970), and The World Almanac Book of Facts, Newspaper Enterprise Association, Inc., New York (1976).

TABLE 12. SUMMARY OF ANNUAL SPENT FUEL SHIPPING DATA

Year	Mass Transported (MT)	Radioactivity Transported (MCi)	Number of Shipments	Average Shipment Distance (Mi)	Shipping Units (10^6 Shipment-Mi)
1976	850	3,820	363	920	0.33
1980	2,400	11,070	1,026	860	0.88
1985	4,970	23,330	2,103	810	1.70
1990	8,640	37,510	3,598	750	2.70
1995	12,990	51,960	5,551	690	3.83
2000	17,680	56,210	7,513	640	4.80
2005	23,130	164,080	9,885	580	5.73
2010	27,100	209,530	11,581	520	6.02
2015	30,900	255,790	13,205	460	6.07
2020	35,200	305,420	15,043	410	6.16

TABLE 13. ANNUAL PLUTONIUM GENERATION IN CHEMICAL REPROCESSING PLANTS

Year	Amount of Plutonium (MT Pu)					
	LWR					
	LWR Without Pu Recycle	LWR With Pu Recycle	Subtotal	HTGR	LMFBR	Total
1975	7.90		7.90			8
1980	19.72	4.40	24.12	2.01		26
1985	33.20	19.23	52.43	0.17		53
1990	67.70	6.05	73.75	0.54	20.36	95
1995	97.46		97.46	1.06	149.75	248
2000	102.67		102.67	1.42	522.75	627
2005	98.95		98.95	1.61	1088.29	1189
2010	86.49		86.49	2.20	1589.64	1678
2015	69.75		69.75	2.60	2119.52	2192
2020	55.80		55.80	3.00	2669.78	2729

The plutonium separated in chemical reprocessing plants will eventually be shipped to fuel fabrication plants for the production of fuel for LWR with plutonium recycle or LMFBR. However, according to the scenario adopted for this study as shown in Table 1, the production of plutonium fuel is not expected to begin until 1978 for LWR and until 1980 for LMFBR. Excess plutonium will be stored until required for use. For the purposes of this study, it is assumed that storage will be at the fuel fabrication plant. All transportation between the chemical reprocessing plant and the fuel fabrication plant is assumed to take place during the same year that the plutonium is generated in the chemical reprocessing plant. Therefore, the quantity of plutonium transported each year is given by the data in Table 13.

The specific activity of the plutonium transported can be calculated from the plutonium data in Table 6 and Table 5. The results have been tabulated in Table 14.

The specific activity of plutonium was applied to the generation data in Table 13 to obtain the amounts of radioactivity transported each year in plutonium shipments. The results of this calculation are tabulated in Table 15.

The AEC (10 CFR71) and DOT (49 CFR173, 178) regulate shipments of fissile fuel to prevent the possible attainment of critical mass or loss of containment by controlling the mass and geometry of fissile material allowed in individual packages and the number of packages allowed in a shipment. In the nuclear fuel cycle, these regulations pertain to movements of enriched uranium, unirradiated fabricated fuel, spent fuel, and recycled plutonium.

Plutonium may be shipped in several container sizes, depending on its isotopic assay, and in several forms: single isotopes or mixtures of isotopes in powder or bulk solid form, as plutonium metal or in dry compounds, usually oxides, of plutonium. Powdered plutonium oxide will probably be the most frequently shipped form since this form is readily incorporated into fuel. Some technical data on possible shipment sizes are included in Table 16. For purposes of this study, two of these sizes are picked for each of truck and rail modes of transportation: a small shipment of 17 packages of the DOT SP 5110 design, with each package containing 4 kgm of plutonium metal, and a large shipment of 133 packages of the DOT SP 5795 design, with each package containing 15.4 kgm of powder composed of at least 60 weight percent Pu-239, less than 1.5 weight percent Pu-241 (a beta emitter), more Pu-240 than Pu-241, and less than 1 weight percent Pu-238.

TABLE 14. SPECIFIC ACTIVITY OF PLUTONIUM

Reactor	Concentration (MCi Pu/MT Heavy Metal)	Assay (Weight Percent Pu)	Specific Activity (MCi Pu/MT Pu)
LWR-U	0.1056	0.93	11.4
LWR-Pu	0.6286	3.08[a]	14.1[b]
HTGR	0.0298	0.10	29.8
LMFBR	0.3640	10.17	3.6

[a] 12.4% of core; balance is LWR-U.
[b] Average.

TABLE 15. RADIOACTIVITY OF ANNUALLY TRANSPORTED PLUTONIUM

Year	Radioactivity of Plutonium (10^3 MCi)					
	LWR-U	LWR-Pu	LWR	HTGR	LMFBR	Total
1975	0.09		0.09			0.09
1980	0.22	0.06	0.28			0.28
1985	0.38	0.27	0.65			0.65
1990	0.77	0.09	0.86	0.02	0.07	0.95
1995	1.11		1.11	0.03	0.54	1.68
2000	1.17		1.17	0.04	1.88	3.09
2005	1.13		1.13	0.05	3.92	5.10
2010	0.99		0.99	0.06	5.72	6.77
2015	0.80		0.80	0.08	7.63	8.51
2020	0.64		0.64	0.09	9.61	10.34

TABLE [illegible]. PLUTONIUM SHIPMENT CAPACITIES

Material	Designation	Mode	Size Data
Plutonium shipped from chemical processing plant to fuel preparation plant			
Metal	Model 2030-1[b,c] DOT SP 5332	Truck or rail	Drum: 0.5 m dia x 0.8 m high Cavity: 25 cm dia x 30 cm high Number of cavities: 2 Shield: Celotex (thermal) Contents of single drum: 4 kgs total in both cavities Number of drums per shipment: 27 (fissile class II), 40 (fissile class III). (other sizes of shipment are also possible.)
Single or mixed plutonium oxides as metal or oxide weight composition: 90% Pu-239 ≤1.5% Pu-241 Pu-240 > Pu-241 <1% Pu-238	Foamglas[a,d] shipping container DOT SP 5795	Truck or rail	Drum: 0.6 m dia x 0.9 m high Cavity: 12 cm dia x 46 cm high Shield: 0.2 m Foamglas (thermal) Contents of single drum: metal: 0.0049 MT Pu-239, 0.0055 MT Pu oxide: 0.0041 MT Pu-239, 0.0046 MT Pu Number of drums per shipment: 120 (other sizes of shipment are also possible.)

[a] Directory of Shipping Containers for Radioactive Materials. United States Atomic Energy Commission. Washington, D. C. October 1968. p. 2A39.10.

[b] Technical Documentation for Model 2030-1 Shipping Container. RFP-1867. Dow Chemical U.S.A., Rocky Flats Division, Golden, Colorado. November 1972.

[c] Reference a, p. 2A31.10.

[d] Special Tests for Plutonium Shipping Containers 6M, SP5795, and L-10. SC-DR-72597. Sandia Laboratories, Albuquerque, New Mexico. September 1972.

Most of the smaller shipments of plutonium will probably go by truck, although a string of rail cars containing small shipments may be both economical and convenient on occasion. The larger shipments are expected to be delivered by rail in the majority of instances. The plutonium transportation scenario for purposes of this study is shown in Table 17. Using this scenario, the annual number of plutonium shipments was calculated from the data in Table 14. The results are shown in Table 19.

TABLE 17. PLUTONIUM TRANSPORTATION SCENARIO

Mode	Use (Percent)	Capacity (MT Pu)
Small Shipment by Truck	40	0.058
Large Shipment by Truck	10	2.012
Small Shipment by Rail	10	0.048
Large Shipment by Rail	40	2.022
AVERAGE	100	0.132

The shipping distance for recycled plutonium refers to the trip between chemical processing plants, where plutonium is separated from other components of spent fuel, and fuel preparation plants, where it is mixed with uranium to fabricate new fuel. The distances between these types of facilities existing in 1973 are given for truck and rail modes in Table 18.

If additional chemical processing plants are built in the vicinities of Salt Lake City, Utah; Dallas, Texas; Cincinnati, Ohio; and St. Paul, Minnesota, and fuel fabrication plants were constructed fairly uniformly throughout the country, the average plutonium shipment distance would decrease from the 1970 value of about 1,000 miles to about 400 miles. The future behavior of this parameter is uncertain. It may stay rather constant if future fuel fabrication plant construction is centered around a few processing plants, or it may decrease nearly to zero if the construction of nuclear parks becomes the vogue. For purposes of this study, the average shipment distance is assumed to decrease linearly from 1,000 miles in 1970 to 400 miles in 2020. The difference between truck and rail is small for 1970 and no significant difference is anticipated between these modes in the future.

TABLE 18. DISTANCES BETWEEN CHEMICAL REPROCESSING PLANTS AND FUEL PREPARATION PLANTS IN 1975

	Distance (mi) to Chemical Reprocessing Plant Sites					
	West Valley, New York		Barnwell, South Carolina		Morris, Illinois	
Fuel Preparation Plant Site	Distance by Truck (mi)[a]	Distance by Rail (mi)[b]	Distance by Truck (mi)[a]	Distance by Rail (mi)[b]	Distance by Truck (mi)[a]	Distance by Rail (mi)[b]
Hematite, Missouri	600	760	750	670	290	320
Crescent, Oklahoma	1,310	1,340	1,130	1,020	650	640
Erwin, Tennessee	650	620	260	460	470	700
Apollo, Pennsylvania	220	200	650	650	540	480
Columbia, South Carolina	720	670	50	65	836	865
Wilmington, North Carolina	760	1,030	260	280	870	1,290
Richland, Washington	2,550	2,560	2,610	2,410	1,930	1,960
AVERAGE	1,030	1,083	946	925	800	921

[a] *Rand McNally Road Atlas: United States, Canada, and Mexico*, 43rd Annual Edition, Rand McNally & Company (1967).

[b] *Rand McNally Handy Railroad Atlas of the United States*, Rand McNally & Company (1971).

A summary of annual transportation data for plutonium is given in Table 19. The number of shipment-miles grows with a doubling time of five years until 2000. After 2005, the growth rate for plutonium production is about 5 percent per year.

TABLE 19. SUMMARY OF ANNUAL PLUTONIUM SHIPPING DATA

Year	Mass Transported (MT)	Radioactivity Transported (MCi)	Number of Shipments	Average Shipment Distance (Mi)	Shipping Units (10^6 Shipment-Mi)
1975	8	90	60	940	0.06
1980	24	280	183	880	0.16
1985	53	650	400	820	0.33
1990	93	950	704	760	0.54
1995	248	1,680	1,887	700	1.32
2000	627	3,090	4,764	640	3.05
2005	1,189	5,100	9,037	580	5.24
2010	1,678	6,770	12,755	520	6.63
2015	2,192	8,510	16,658	460	7.66
2020	2,729	10,340	20,737	400	8.29

ANNUAL TRANSPORTATION OF HIGH LEVEL RADIOACTIVE SOLID WASTE

The quantities of high level radioactive solid waste are functions of the total heavy metal weight in the fuel charged to the chemical processing plants (References 2, 6).

All the solid waste is assumed to be stored at the chemical processing plants for ten years before it is shipped to the Federal Waste Repository. The annual volumes of high level waste to be transported are calculated using the data in Table 4. The results are displayed in Table 20 and Figure 13.

TABLE 20. ANNUAL TRANSPORTATION REQUIREMENTS FOR HIGH LEVEL RADIOACTIVE SOLID WASTE

Year	Amount of High Level Radioactive Solid Waste (10^3 ft^3)[a]					
	LWR					
	LWR Without Pu Recycle	LWR With Pu Recycle	Subtotal	HTGR	LMFBR	Total
1985	1.7		1.7			1.7
1990	4.2	0.5	4.7	0.1		4.8
1995	7.1	2.4	9.5	1.0		10.5
2000	14.6	0.7	15.3	3.5	0.5	19.3
2005	21.0		21.0	5.7	4.4	31.1
2010	22.1		22.1	8.5	15.3	45.9
2015	21.3		21.3	10.9	32.0	64.2
2020	17.5		17.5	13.1	48.7	79.3

[a] Specific volumes of wastes from various spent fuels (Reference 6) are:

Fuel	Specific Volume of Waste (ft^3/MT)
LWR - No Pu Recycle	2
LWR - Pu Recycle	2
HTGR	6
LMFBR	3

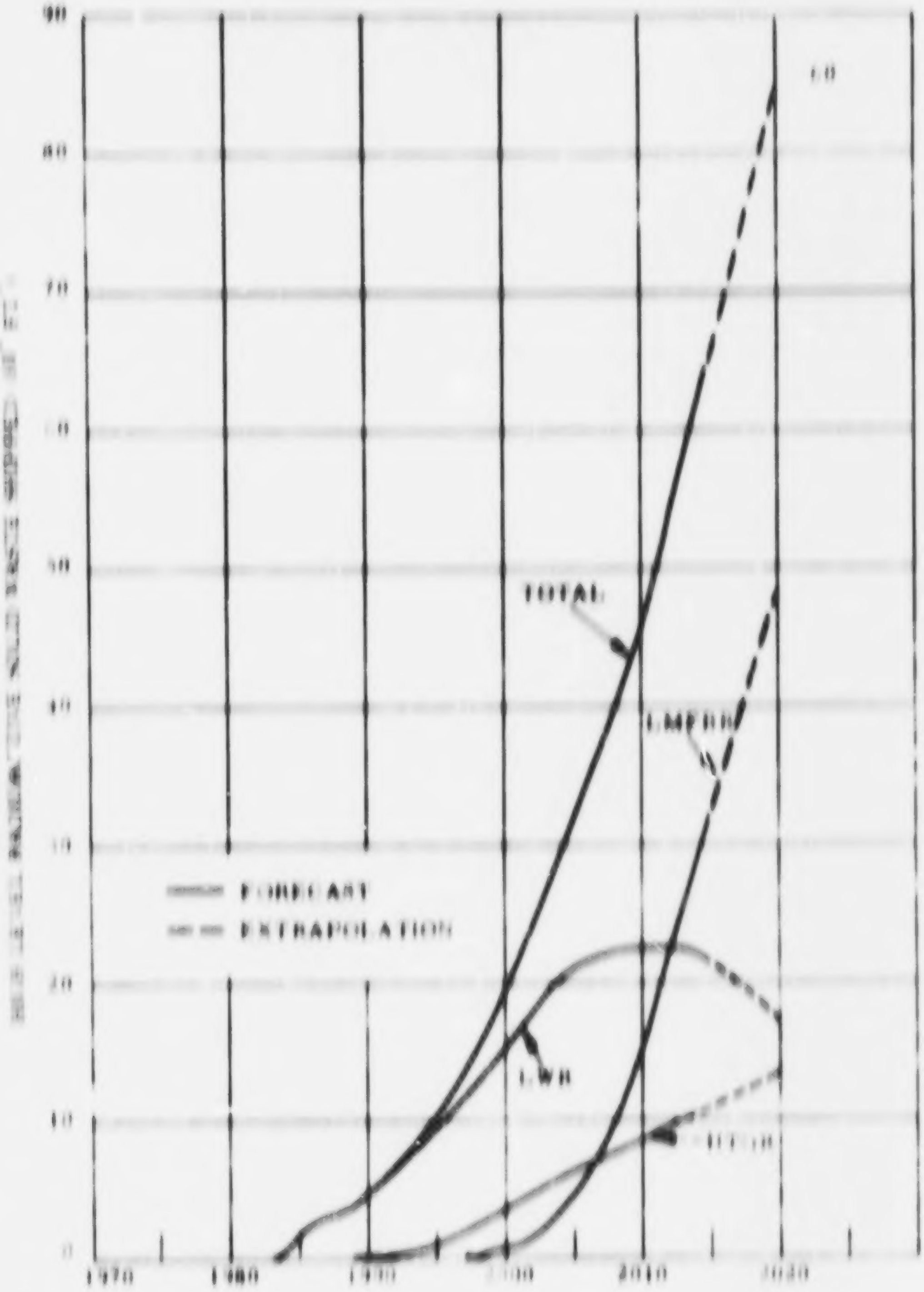

FIGURE 11. PROJECTION OF HIGH-LEVEL RADIOACTIVE SOLID WASTE SHIPPING REQUIREMENTS

The total amount of high level waste accumulated over 50 years is about 1.5 million ft^3. This amount of waste would occupy about 30 acres, assuming the allotment rate of 1 acre/50,000 ft^3 given by a commercial burial operation (Reference 6). This allotment rate actually applies to solid waste other than high level waste, and is used here only to indicate that the total quantity is small.

The radioactivity contents of high level radioactive solid waste produced from processing a metric ton of fuel from the different reactors under consideration are given in Table 6. Combining this information with the data in Table 20, the annual amounts of radioactivity transported in the form of high-level radioactive solid waste are calculated and tabulated in Table 21.

Technical data describing shipment capacities for high level radioactive solid waste are given in Table 22. The container which will most likely be used for transportation and storage purposes is the one with largest capacity, 1.6 m^3 (56.5 ft^3) shipment.

Since the Federal Waste Repository will most likely be located in the western United States, where population density is lowest, the shipping distances for high-level waste transportation will be long. For this reason, most of the waste will probably be shipped by rail, since long-haul traffic is more convenient by rail than by truck. For purposes of this study, 75 volume percent of the waste is assumed to be shipped by rail and 25 volume percent by truck, each with a capacity of 56.5 ft^3 per shipment. Using this scenario, the annual number of high-level radioactive solid waste shipments was calculated from the data in Table 20. The results are shown in Table 24.

Probably only one Federal Waste Repository, but possibly two, will be built in the next 50 years. The three sites used in Table 23 appear to be good candidates for such a facility. Distance data for high level waste shipments made in the near future to these sites are given in Table 23.

The average distance is 2,130 miles by truck or 2,190 miles by rail; for the purposes of this study, these values were adopted for the period 1970-2000. By year 2000, construction of chemical processing plants is expected for the southwestern and western United States. If they are built within the vicinities of Dallas, Texas, and Salt Lake City, Utah, the average distance will be 1,720 miles by truck and 1,640 miles by rail; these values were adopted for the purposes of this study for the period 2000-2020.

TABLE 21. RADIOACTIVITY OF ANNUALLY TRANSPORTED HIGH-LEVEL RADIOACTIVE SOLID WASTE

Year	Radioactivity of High Level Waste (10^3 MCi)[a]					
	LWR					
	LWR Without Pu Recycle	LWR With Pu Recycle	Subtotal	HTGR	LMFBR	Total
1985	0.26		0.26			0.26
1990	0.63	0.12	0.75	0.02		0.77
1995	1.06	0.60	1.66	0.20		1.86
2000	2.19	0.18	2.37	0.70	0.10	3.17
2005	3.15		3.15	1.14	0.88	5.17
2010	3.32		3.32	1.70	3.06	8.08
2015	3.20		3.20	2.18	6.40	11.78
2020	2.62		2.62	2.66	9.74	15.02

[a] Specific radioactivity levels of wastes from various spent fuels are:

Fuel	Specific Activity of Waste (MCi/ft^3)
LWR - No Pu Recycle	0.15
LWR - Pu Recycle	0.25
HTGR	0.20
LMFBR	0.20

TABLE 11. SHIPMENT CAPACITIES FOR HIGH-LEVEL RADIOACTIVE SOLID WASTE

Material	Designation	Mode	Size Data
Shipment of high-level radioactive solid waste from chemical process plant to Federal Waste Repository	CE cask 701 or 702[a] DOT SP pending	All	Cask: 1.5 m dia x 1.6 m high Cavity: 0.4 m dia x 1.0 m deep Volume of contents: 0.13 m^3 Shield: 0.3 m Pb Radioactivity of contents: 10^5 Ci Number of casks per shipment: 1
	Salt vault cask[b]	Truck	Cask: 1.1 m dia x 3.4 m long Cavity: 0.5 m dia x 2.3 m long Shield: stainless steel interior, steel exterior 0.2 m (equivalent) Pb Number of canisters: 8 Radioactivity of contents: 1.855 MCi Number of casks per shipment: 1
	Not available[c]	Truck, rail, or barge	Cask: 1.5 m dia x 3.7 m long Cavity: 1.2 m dia x 3.1 m long Shield: carbon steel interior with water channels 0.2 m Pb, 0.04 m carbon steel Canister: 0.3 m dia x 3.0 m long Volume of canister contents: 0.18 m^3 Number of canisters: 9 Volume of cask contents: 1.6 m^3 Number of casks per shipment: 1

[a] Directory of Shipping Containers for Radioactive Materials. United States Atomic Energy Commission. Washington, D. C. October 1969.

[b] Reference a.

[c] Blomeke, J. O. Magnitude of the Waste Management Problem. Oak Ridge National Laboratory. Lecture given at UCLA. ORNL-DWG-71-3841. July 1972.

TABLE 23. DISTANCES BETWEEN CHEMICAL PROCESSING PLANTS IN 1975 AND POSSIBLE FEDERAL WASTE REPOSITORIES

Chemical Processing Plant Site	Transport Mode	Distance to Selected Federal Waste Repository Sites (Mi)		
		Nevada	Hanford	New Mexico
West Valley, New York	Truck[a] Rail[b]	2,560 2,570	2,550 2,570	1,860 1,980
Barnwell, South Carolina	Truck Rail	2,640 2,720	2,810 2,860	1,460 1,560
Morris, Illinois	Truck Rail	2,000 2,000	1,930 1,960	1,380 1,500
AVERAGE	Truck Rail	2,400 2,430	2,430 2,463	1,567 1,680

[a] *Rand McNally Road Atlas: United States, Canada, and Mexico*, 43rd Annual Edition, Rand McNally & Company (1967).

[b] *Rand McNally Handy Railroad Atlas of the United States*, Rand McNally & Company (1971).

TABLE 24. SUMMARY OF ANNUAL SHIPPING DATA FOR HIGH-LEVEL RADIOACTIVE SOLID WASTE

Year	Volume Transported (ft^3)	Radioactivity Transported (MCi)	Number of Shipments	Average Shipment Distance (Mi)	Shipping Units (10^6 Shipment-Mi)
1985	1,700	260	31	2,175	0.07
1990	4,800	700	87	2,175	0.19
1995	10,500	1,860	189	2,175	0.41
2000	19,300	3,170	348	2,175	0.76
2005	31,100	5,170	560	1,810	1.01
2010	45,900	8,080	827	1,810	1.50
2015	64,200	11,780	1,156	1,810	2.09
2020	79,500	15,025	1,431	1,810	2.59

The summary of annual transportation data for high level waste appears in Table 24.

ANNUAL TRANSPORTATION OF GASEOUS FISSION PRODUCTS

Some fission products are in the form of gas. Reference to Table 6 indicates that krypton and xenon are the predominant gaseous radionuclides at the time of processing. The other radioactive gases have essentially decayed away by the time of processing. Since krypton and xenon belong to a family of chemically inert species called noble gases, the gaseous fission products are called noble gases.

The longest lived component of fission gases is Kr-85, which has a half life of 10.7 years, which makes it the most significant gaseous radionuclide in nuclear fuels. One possible management strategy for the gaseous wastes is to store them temporarily and then release them to the atmosphere. In this study, the premise is adopted that such release provides an unacceptable solution and shipments of fission gases are assumed to be part of the transportation scenario (Reference 22). Research is being conducted to find a feasible method of entraining the gases in a solid matrix for transport purposes. When such solidification processes are available, the shipments of gases would be counted as shipments of high level radioactive solid wastes. Such shipments would probably be safer than shipments of pressurized cylinders of gas since the amount of gas released in an accident would be much less. For purposes of estimating the risk, the management of gaseous waste is assumed to include transport of gases in pressurized cylinders and not release to the atmosphere of the gases produced in fission or chemical processes. All of the gaseous waste is assumed to be stored at the chemical processing plants for ten years before it is shipped to the Federal Waste Repository. The radioactivity of the fission-product gases at the time of shipping was calculated from the radioactivity of the various spent fuels at time of processing in Table 6. The radioactivity that may be transported annually in the form of pressurized cylinders of radioactive gas was calculated. The results are given in Table 25.

Technical data describing the containers and shipment capacities for noble gas are presented in Table 26. The container adopted for the purposes of this study consists of 6 cylinders holding 0.18 MCi each. The annual number of cylinders of gas to be transported was calculated from the annual radioactivity data in Table 24. The results are presented in Table 27.

TABLE 25. RADIOACTIVITY OF ANNUALLY TRANSPORTED NOBLE GAS

	Radioactivity of Noble Gas (MCi)[a]					
	LWR					
Year	LWR Without Pu Recycle	LWR With Pu Recycle	Subtotal	HTGR	LMFBR	Total
1985	5		5			5
1990	13	1	14	1		15
1995	22	5	27	6		33
2000	45	2	47	19	1	67
2005	64		64	34	7	105
2010	68		68	47	25	140
2015	65		65	60	53	178
2020	57		57	73	77	207

[a] After 10 years storage.

Fuel	Fission Product Gases (Percent Radioactivity)
LWR - No Pu Recycle	0.136
LWR - Pu Recycle	0.074
HTGR	0.718
LMFBR	0.049

TABLE 26. SHIPMENT CAPACITIES FOR NOBLE GAS

Material	Designation	Mode	Size Data
Gaseous Fission Products Shipped from Chemical Process Plant to Federal Waste Repository	Gas Shipping[a] Container BE 376	Truck Rail Barge	Drum: 0.6 m dia x 1.1 m long Cavity: 0.3 m dia x 0.8 m long Shield: 0.15 m Phenolic Foam 0 to 8 cm Pb Cylinder: 10 cc to 5l Radioactivity of Contents: 1000 Ci Number of Drums per Shipment: 1
	Not Available[b]	Truck Rail Barge	Cask: Structure with 2 cm steel wall large enough to contain 6 standard 3W (2200 psi) cylinders in hexagonal array Shield: Steel raschig rings, water Radioactivity in Cylinder Contents: 0.39 MCi Number of Cylinders per Shipment: 6

[a] Directory of Shipping Containers for Radioactive Materials. United States Atomic Energy Commission. Washington, D. C. October 1968.

[b] Blomeke, J. O. Magnitude of the Waste Management Problem. Oak Ridge National Laboratory. Lecture given at UCLA. ORNL-DWG-71-3839. July 1972.

TABLE 27. SUMMARY OF ANNUAL SHIPPING DATA FOR NOBLE GAS

Year	Radioactivity Transported (MCi)	Amount Transported (Cu ft)	Number of Shipments	Average Shipment Distance (Mi)	Shipping Units (10^6 Shipment-Mi)
1985	5	29	5	2,175	0.01
1990	15	84	14	2,175	0.03
1995	[illegible]	184	31	2,175	[illegible]
2000	[illegible]	[illegible]	63	2,175	0.11
2005	105	584	98	1,810	0.18
2010	140	776	130	1,810	0.24
2015	176	[illegible]	165	1,810	0.30
2020	207	1150	192	1,810	0.35

Transportation of noble gas is expected to have the same scenario as that of high-level solid waste, since noble gas is a waste product that is destined for storage in the Federal Waste Repository. The use frequencies of truck and rail modes of transport and the average shipment distances of high-level waste transportation are adopted for noble gas transportation. The summary of annual transportation data for noble gases is given in Table 27.

SUMMARY

The transportation activity data in Tables 12, 19, 24, and 27 are represented graphically in Figure 14. Nuclear power transportation activity exceeds one million miles in 1980 and ten million miles after 2000. Up until about year 2005, spent fuel transportation will dominate. Plutonium transportation increases dramatically after 1995 and exceeds spent fuel transportation after 2005.

The transportation of radioactive waste does not exceed ten percent of the total nuclear power transportation activity until after the year 2000. Shipments of radioactive gases comprise less than two percent of the transportation activity.

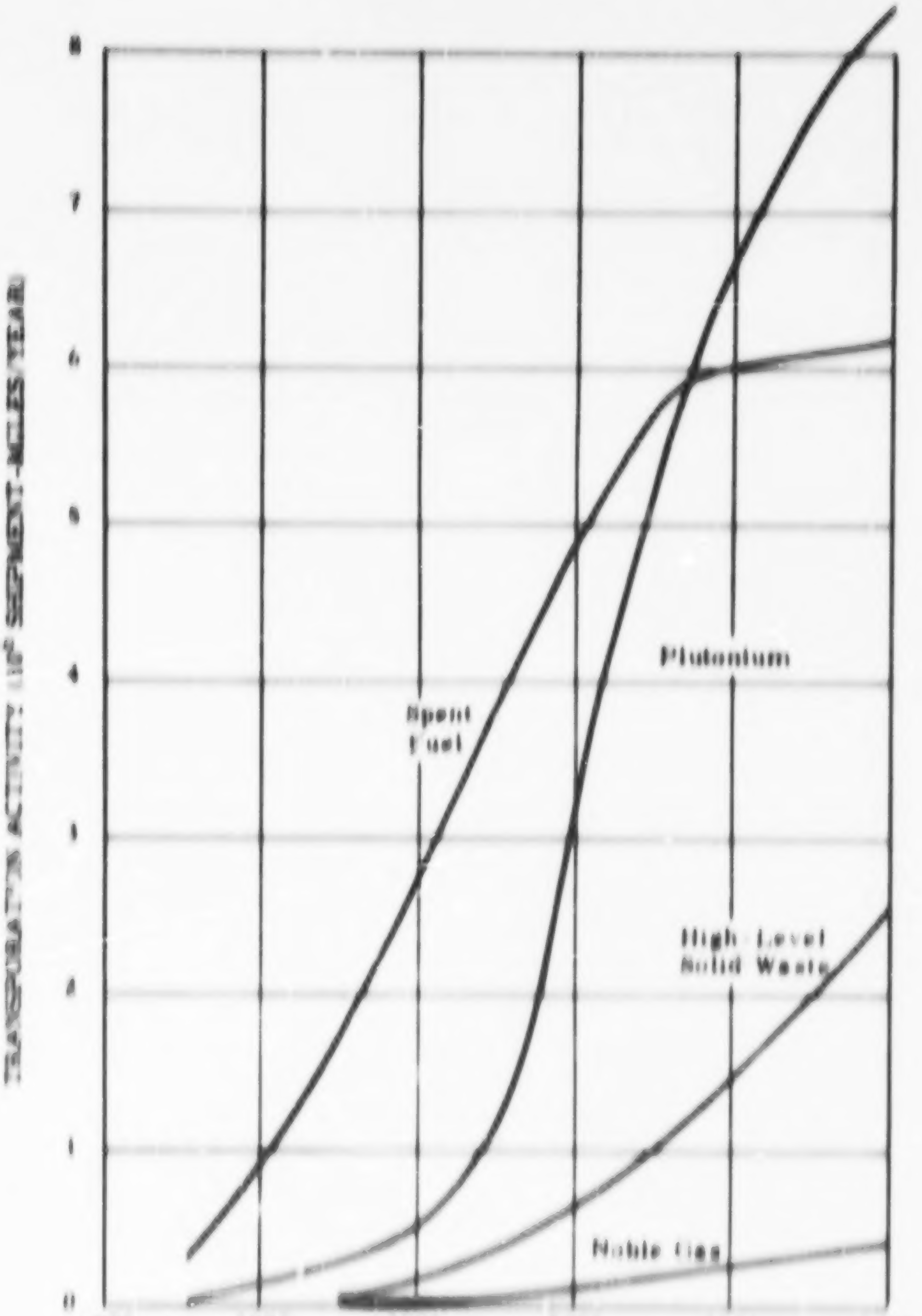

FIGURE 14. SUMMARY OF ANNUAL TRANSPORTATION ACTIVITY

SECTION VI

TRANSPORTATION ACCIDENT RISKS

INTRODUCTION

One risk associated with the shipment of radioactive materials from the nuclear power industry is the release of radioactivity from the shipment package as a result of an accident during transportation. However, there is very little statistical data on which to assess this risk. Within the United States over the past 25 years, there have been about 300 reported accidents in transportation involving packages of all kinds of radioactive material. About 10% of those accidents involved release of radioactive material from medical and industrial radiochemicals. None resulted in perceptible injury or death attributed to the radiation aspects. There have been no releases from nuclear power shipments.

At present, shipments of radioactive materials in the nuclear power industry move in routine commerce on conventional transportation equipment. Therefore, shipments are subject to the same transportation environment, including accidents, as nonradioactive cargo. Consequently, the frequency and severity of accidents involving shipments of radioactive materials can be estimated from accident statistics involving the transportation of nonradioactive materials.

The public may receive a radiation exposure from a transportation accident if radioactivity is released from the shipment package. For the purposes of this study, it is assumed that if the package containing radioactive material is sufficiently damaged, there will be a release of radioactivity. Therefore, the risk of this release can be directly related to the probability and severity of damage to the package. This damage is related to the severity of the accident, the form and amount of energy sustained by the package as a result of the accident, and its ability to withstand those forces. This ability is a function of packaging design.

This section describes transportation accidents risks. The parameters to be estimated are the probability and severity of accidents by transportation mode, the probability and severity of damage to the package, and the probability of release of radioactive materials. The probability and severity of accidents will be based on reported statistics for commercial vehicles. Each accident is described by a sequence of events which can damage the package and thus lead to the release of radioactivity. The combinations of events necessary for release is described by a fault tree. Each event in the sequence is a statistical variable which could be described by a probability distribution if enough information were available. In this report, best estimate values are used as input data. The probability of release in a shipment accident is determined by fault tree analysis.

ACCIDENT PROBABILITY AND SEVERITY

The probability and severity of accidents to shipments of radioactive materials depends on the characteristics of the transport vehicles. In this study, the shipments are expected to go by truck, rail, and barge on paths that are used also for shipments of other products of commerce, industry, and defense. Accident statistics for these transport vehicles maintained by Federal agencies, such as the Department of Transportation and the Coast Guard, provide readily available estimates of the accident probabilities for nuclear shipments. Specific values of these probabilities are shown in Table 28.

TABLE 28. PROBABILITIES OF ACCIDENTS

Mode	Probability[a] $[(10^6 \text{ Shipment-Miles})^{-1}]$
Truck	1.69
Rail	0.7
Barge	1.8

[a] Reference 14.

The accident statistician recognizes three broad categories of traffic accidents: collisions, noncollisions, and other events. Collisions involve interactions of the transport vehicle with other objects, whether moving vehicles or fixed objects. Noncollisions are accidents in which the transport vehicle leaves the transport path or deviates from normal operation in some way, such as by rolling over on its top and side. Accidents classed as other events include personal injuries suffered on the vehicle, records of persons falling from or being thrown against a standing vehicle, cases of stolen vehicles, and fires occurring on a standing vehicle. The probabilities with which these categories of events have been observed in truck and rail freight accidents are indicated in Table 29.

All these accidents may involve conditions which lead to damage of the cargo. In particular, physical forces arising from impact, puncture, vibration, and fire events tend to reduce either the ability of the shipment

TABLE 29. ACCIDENT FREQUENCY STATISTICS

Parameter	Mode	Magnitude	Fraction of Accidents[a]		
			Collision	Noncollision[b]	Other[c]
Speed	Truck	0-30 mph	0.221	0.008	
		30-50 mph	0.422	0.065	
		50-70 mph	0.153	0.022	
		>70 mph	0.005		
	TOTAL		0.801	0.095	0.104
	Rail	0-30 mph	0.123	0.410	
		30-50 mph	0.067	0.224	
		50-70 mph	0.020	0.065	
		>70 mph	0.0002	0.001	0.090
	TOTAL		0.210	0.700	0.090
Fire Duration	Truck	0 hr		0.98430	
		<0.5 hr		0.01556	
		0.5-1 hr		0.00012	
		>1 hr		0.00001	
	Rail	0 hr		0.98500	
		<0.5 hr		0.01275	
		0.5-1 hr		0.00210	
		>1 hr		0.00015	

[a] Based on data from Reference 14.

[b] Noncollision accidents for trucks are classified as run-offs and roll-overs, while for rail transport, they are classified as derailments.

[c] Other accidents include events assumed to be of no significant to release of radioactivity.

package to contain radioactivity and shield radiation or the ability of the package to dissipate heat or both. The ability of the materials and structures in the shipment package to resist these forces depends on the magnitudes of the forces. These magnitudes vary with the severity of the accident, as does the frequency with which they occur. The variation of the frequency of accident severity can be formulated on the basis of accident experience in the cases of truck and rail transport, but less data is readily available in the case of barge transport.

The statistical data indicate that collision and noncollision truck and rail accidents may be classified into four ranges of vehicle speeds. In addition, all accidents may be classified into four ranges of time duration of fires that may or may not break out. For convenience, one of these time ranges is defined so as to describe all those accidents that do not involve fire. The compositions with respect to these parameters of the frequency of collision and noncollision accidents to truck and rail freight shipments are given in Table 29.

The partition of the entire set of freight traffic accidents into severity classes is somewhat arbitrary. In this report, all accidents have been divided into one of three severity classes. Minor accidents include those collisions and noncollisions at low speed and short duration of fire and those other accidents with short fires. Moderate accidents include combinations of speed and fire of intermediate intensity. Severe accidents include combinations of speed and fire of large intensity. The data in Table 29 have been classified in Table 30. Barge accident probabilities have been classified on the basis of the duration of fires and actual data on cargo damage in Reference 7.

TABLE 30. ACCIDENT SEVERITY CLASSES

Severity	Speed	Fire	Fraction of Accidents[a]		
			Truck	Rail	Barge
Minor	0-30 mph	0-1/2 hr	0.229	0.531	
	30-50 mph	0	0.479	0.287	
	Other	0-1/2 hr	0.104	0.090	
TOTAL			0.812	0.908	0.900
Moderate	0-30 mph	1/2-1 hr		0.002	
	30-50 mph	0-1/2 hr	0.008	0.004	
	50-70 mph	0-1/2 hr	0.175	0.085	
	Other	1/2-1 hr			
TOTAL			0.183	0.091	0.080
Severe	0-30 mph	>1 hr			
	30-50 mph	1/2->1 hr			
	50-70 mph	1/2->1 hr			
	>70 mph	0->1 hr	0.005	0.001	
	Other	>1 hr			
TOTAL			0.005	0.001	0.020

[a] Fractions less than 0.001 are not entered in table.

CONTAINMENT FAILURE IN SHIPMENT ACCIDENTS

In order for the public to be exposed to radioactive material contained in the shipping containers, at least one of several possible sequences of events must occur. The shipping containers may be represented as concentric series of envelopes. Each envelope must be broken in some way to provide a pathway for the radioactive contents to spill outside the container. Even if a pathway to the environment is provided, a physical force must be available to drive the contents outside. Evaluation of the probability of occurrence of these accidental conditions is facilitated by fault tree analysis. The shipping container is represented by a fault tree diagram, which shows the logical relationships between barriers that must be faulted and pathways that must be provided for releases to occur. Probability values are attached to each of the primary events represented in the fault tree diagram.

Mechanisms Leading to Containment Failure

The principal mechanisms in an accident which may initiate sequences of events leading to containment failure used in this report are:

1. Impact.
2. Puncture.
3. Thermal mode.
4. Vibration.
5. Equipment failure.
6. Human error.

Although the list is not exhaustive, these mechanisms are the primary events used in the fault trees for each shipping container.

The probabilities of impact and puncture for truck and rail accidents are estimated directly from accident statistics. The probability of impact is assumed to be the fraction of accidents denoted by collisions. In the noncollision category, which for truck accidents includes run-offs and roll-overs and for rail accidents includes derailments, the shipment package is more likely to encounter sharp objects than in collisions or other accidents. Thus, the probability of puncture is assumed to be the fraction of accidents denoted by noncollisions. It is assumed that both impact and puncture can occur as a result of a barge accident. The probabilities of impact and puncture for barge accidents were estimated by engineering judgement.

Failure in the thermal mode requires a high temperature environment for the shipping container. Two causes of high temperature are recognized: a heat source outside the container and a heat source inside the container. The external heat source is provided by the cargo when the cooling capability of the shipment package has been impaired. The probability of an external heat source is estimated from the incidence of fires in the accident statistics.

The information gain from accident statistics can be formulated to reflect the conditional probability of events as a function of accident severity. In particular, the conditional probabilities of impact, puncture and external heat source can be estimated. For example, the conditional probability of impact, given an accident of a specific severity, is the fraction of accidents of that severity which are collisions. Other conditional probabilities are evaluated similarly. The results are presented in Table 31.

TABLE 31. CONDITIONAL PROBABILITIES OF IMPACT, PUNCTURE, AND FIRE

Mode	Accident Severity	Probability	Conditional Probability[a]		
			Impact	Puncture	Fire
Truck	Minor	0.812	0.761	0.097	0.006
	Moderate	0.183	0.874	0.126	0.057
	Severe	0.005	0.987	0.002	0.011
Rail	Minor	0.908	0.208	0.193	0.009
	Moderate	0.091	0.234	0.763	0.068
	Severe	0.001	0.194	0.800	0.449
Barge[b]	Minor	0.90	0.20	0	0
	Moderate	0.08	0.50	0.30	0.0065
	Severe	0.02	1.00	0.80	0.065

[a] Derived from Tables 29 and 30, this report.

[b] Impact and puncture numbers estimated by engineering judgment.

Accident statistics are not available for vibration, equipment failures and human error. The conditional probabilities of vibration, equipment failures and human error for severe accidents are taken from another study (Reference 15). As conservative estimates, the probabilities are assumed to be the same for minor and moderate accidents. This study does not include the release pathway described by diffusion of radioactivity through a barrier because little information on the phenomena is available and the release rates are small.

Description of Shipping Containers

Shipping containers that are expected to be used for transporting spent fuel, recycled plutonium, high level radioactive solidified waste, and fission gases were selected for fault tree analysis. Schematic diagrams for these containers are presented in Figures 15 through 18.

The diagram for the spent fuel shipping container in Figure 15 is a simplified schematic description of the General Electric IF 300 cask (Reference 16). Briefly, the cask consists of a fuel cavity lined with a steel shell, surrounded by a gamma shield of depleted uranium and an outer steel shell. The fuel is cooled with water or solution inside the cavity. Outside the outer shell, the cask is fitted with a jacket of water, which serves to shield the public from fast neutron fluxes and to further cool the cask. Additional cooling by circulation of air is provided, but since such a blower system presents no significant barrier to radioactive material release, and since the cask is designed to withstand the thermal rigors of the heat load from both the fuel and the sun on a 130°F day without the benefit of these auxiliary blowers (Reference 16), this blower system is disregarded in the fault tree diagram.

Essentially, the cask may be regarded as a double containment of the fuel. The cladding provides one barrier and the combination of inner shell, gamma shield, and outer shell provides the other. The second barrier may be penetrated through one of three paths: blowdown of the pressure relief valve, loss of sealing capability of the closure head, and breachment of the cask. Breachment of the cask is considered to require breachment of each of two subbarriers: the inner shell and the layer of combined shield and outer shell. Neither the primary coolant fluid in the cavity nor the neutron shield water and jacket are regarded as significant barriers to material release.

The diagram for the recycled plutonium shipping container in Figure 16 is a simplified schematic description of the Dow Chemical Model 2030-1 container (Reference 17). Briefly, the container consists of a 10-gallon drum lined with boards of Celotex insulation. The Celotex boards are cut

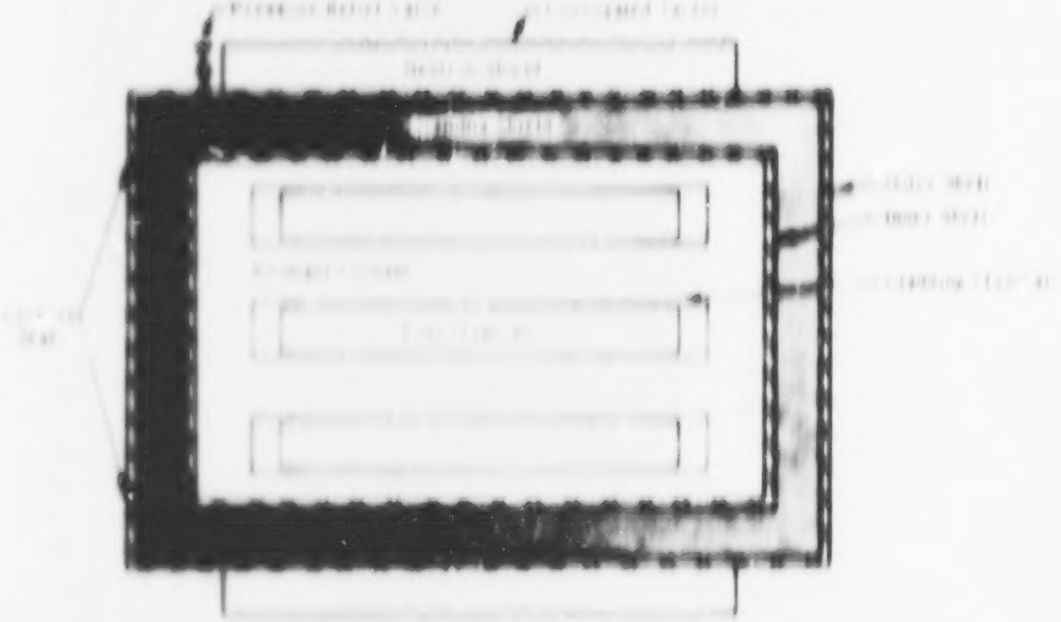

FIGURE 15. SCHEMATIC DIAGRAM OF SPENT FUEL SHIPPING CONTAINER

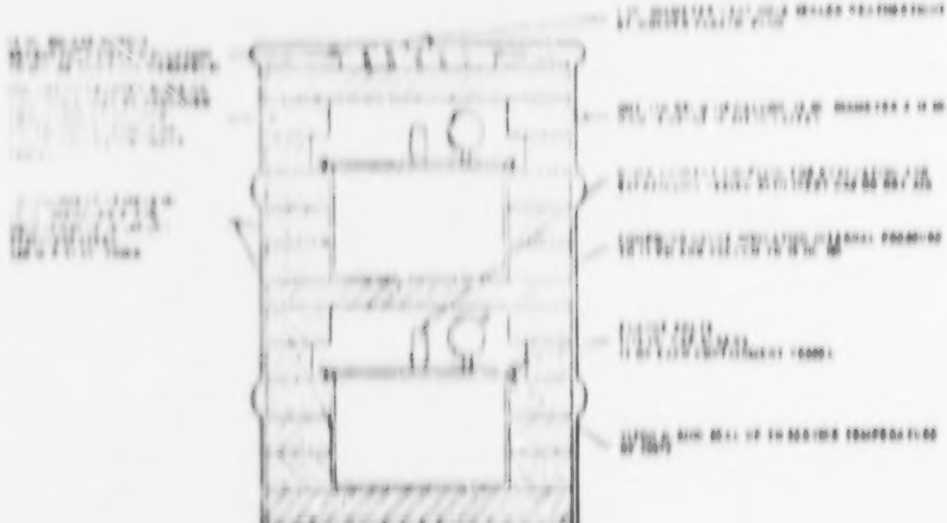

FIGURE 16. SCHEMATIC DIAGRAM OF RECYCLED PLUTONIUM SHIPPING CONTAINER

into rings and can be arranged to form a single large cavity to accommodate a large containment vessel, or to form two smaller cavities to accommodate two small containment vessels.

In this container, the plutonium must penetrate three barriers to reach the atmosphere: the containment vessel, the Celotex insulation, and the drum. Pathways may be provided by a break in the vessel walls or the loss of seal at the interface of the vessel lid and the vessel wall, by breakage, slippage, or warping of the Celotex boards, and breakage, loss of seal at the edge of the lid, or removal of the molded plastic plug in the lid vent opening of the drum.

In Figures 17 and 18, schematic diagrams are shown for possible shipping containers for high level radioactive solidified waste and gaseous fission products based on Oak Ridge National Laboratory designs (Reference 10). These containers are similar to spent fuel shipping containers in that the materials are packed in individual elements which are mounted in a shielded, cooled cask. In the case of spent fuel, the elements are contained by cladding and end boxes, whereas the waste products elements are contained by metal cans or cylinders.

Container Damage and Release Probability

The probability and severity of damage to a container in an accident is related to the severity of the accident, the form and amount of force applied to the container as a result of the accident and the ability of the container to withstand those forces. The form and amount of force transmitted to the package in an accident depend on the design features of the transport vehicle and the mounting of the container on the vehicle. The ability of the container to withstand these forces resulting from the accident depends on the design of the container.

The severity of container damage in an accident determines the size of the release pathway formed and thus, the quantity of radioactivity released to the environment. In this study, three discrete values of the container damage severity were postulated: small, medium and large. Container damage consisting of microscopic openings such as hairline cracks and pinholes is considered to be small damage severity. Medium damage severity is taken to be openings on the order of the size of a fill port. An opening several times larger than a fill port is assumed to be large damage severity.

Estimates have been made elsewhere of the fraction of containers expected to be damaged and the severity of that damage for various accident severity classes (Reference 7). Some of the accidents result in

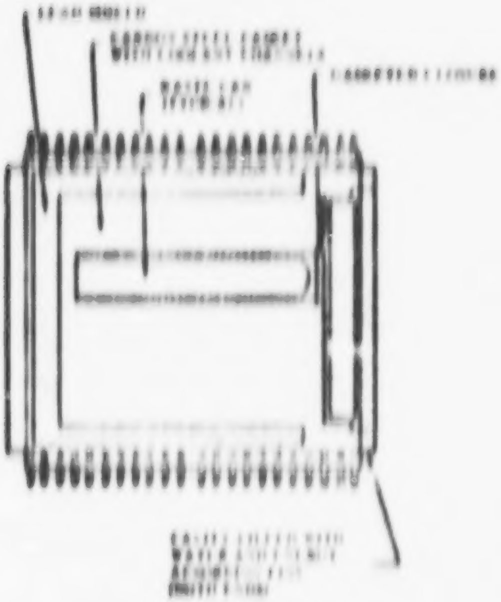

FIGURE 17. SCHEMATIC DIAGRAM OF HIGH LEVEL RADIOACTIVE SOLIDIFIED WASTE SHIPPING CONTAINER

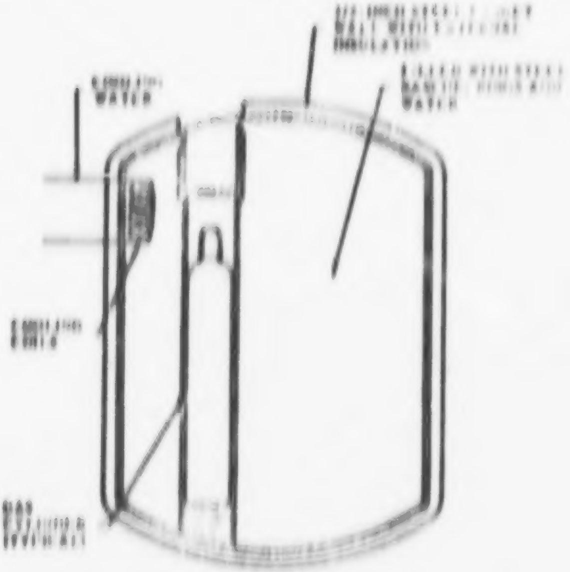

FIGURE 18. SCHEMATIC DIAGRAM OF FISSION GAS SHIPPING CONTAINER

no breach of containment and thus, no release of radioactivity to the environment. This integrity has been attributed to Federal regulations which include testing requirements for containers used for the shipment of radioactive materials.

In this study, the probability of release of radioactivity is assumed to be directly related to the probability and severity of damage to the container. The release severity is thus classified as small, medium and large corresponding to the discrete values of container damage severity. The conditional probability of release as a function of accident severity is estimated by fault tree analysis. Because accident statistics are not available, the conditional probabilities of release are assumed to be constant with accident severity.

Fault Tree Diagrams and Data

Fault tree diagrams of the spent fuel and plutonium shipping containers are shown in Figures 19 and 20, respectively. The fault tree in Figure 21 applies to both high-level radioactive solid waste and noble gas shipping containers. Each fault tree identifies the combinations and sequences of events which must occur for the release of radioactivity.

Fault tree input data for the spent fuel shipping container are presented for each of the three transportation modes in Tables 12, 13, and 14. The data are numbered sequentially corresponding to the numbers on the fault tree diagram of Figure 19. Six mechanisms are identified corresponding to the principal accident mechanisms leading to failure of a containment barrier.

The first entry for each mechanism is the conditional probability of occurrence of the mechanism given an accident of a specific severity. Subsequent entries are the conditional probabilities of release of a specific severity given that the mechanism has actually occurred in an accident of specified severity. These entries are the probabilities of barriers yielding to the force of a mechanism, the so-called inhibit gate probabilities. The probability data were adopted from Reference 15. The barriers are arranged in the tables from inside the container outward as much as possible, although certain pathways, such as pressure relief valve lines and closure seals, may span two or more barriers. Basic fault tree input data for each of the fault trees for the remaining shipping containers and their associated transportation modes are presented in Tables 15, 16, 17, and 18. The input data for noble gas shipping containers are assumed to be the same as for solid waste containers, since their fault trees are similar and the inhibit gate probability information is not established well enough to distinguish between the two containers.

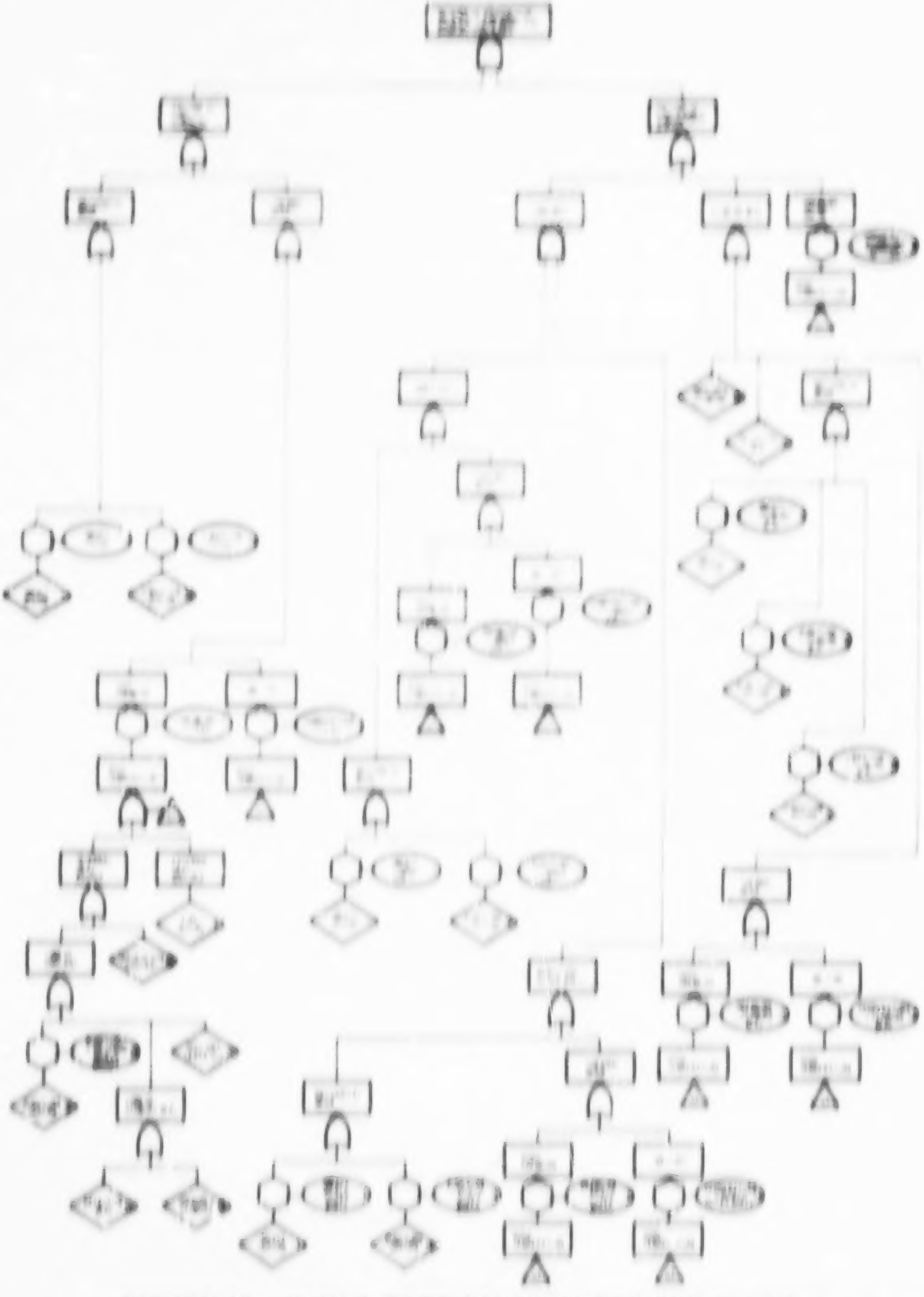

FIGURE 19. FAULT TREE DIAGRAM FOR SPENT FUEL SHIPPING CONTAINER

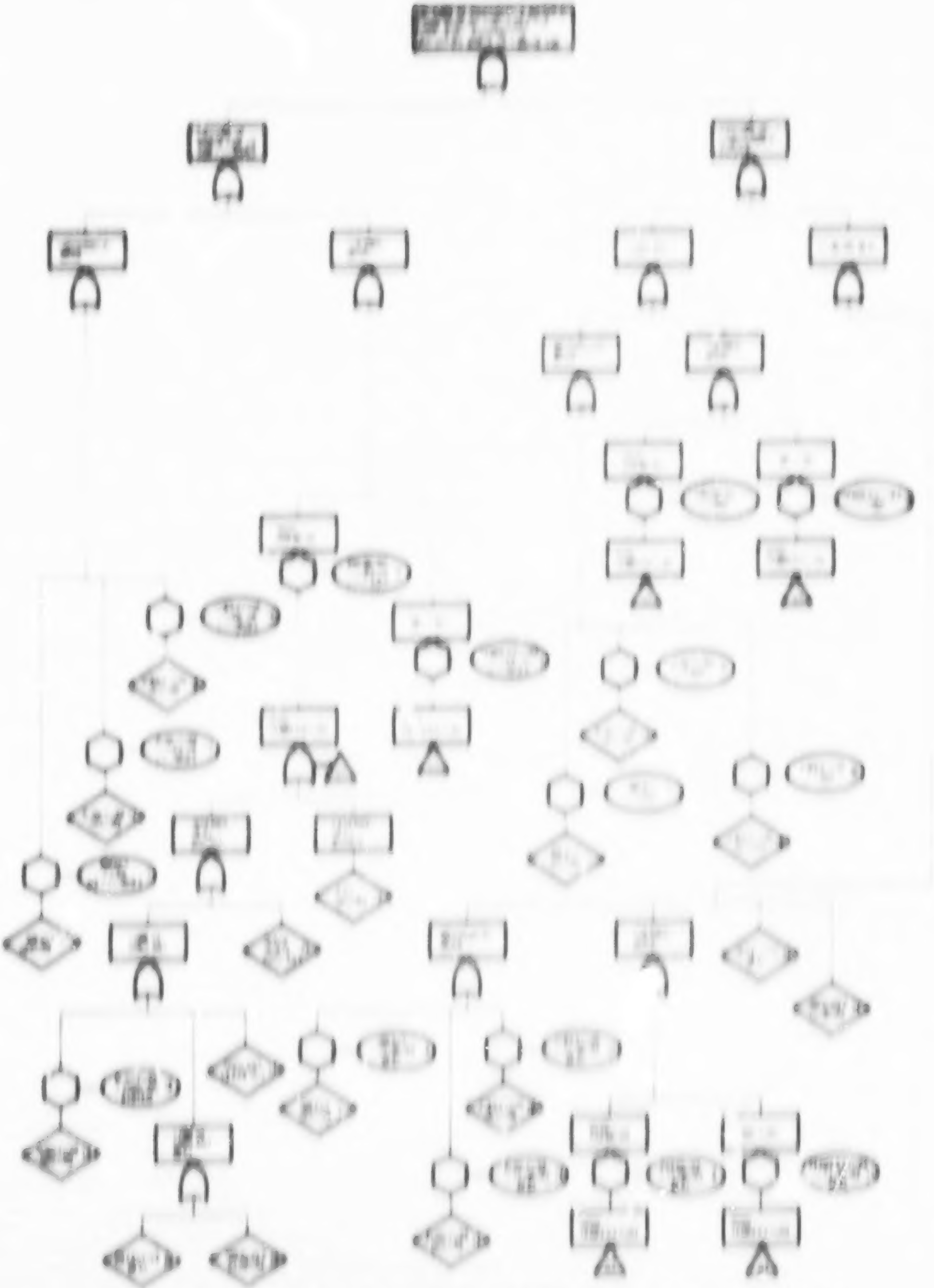

FIGURE 20. FAULT TREE DIAGRAM FOR PLUTONIUM SHIPPING CONTAINER

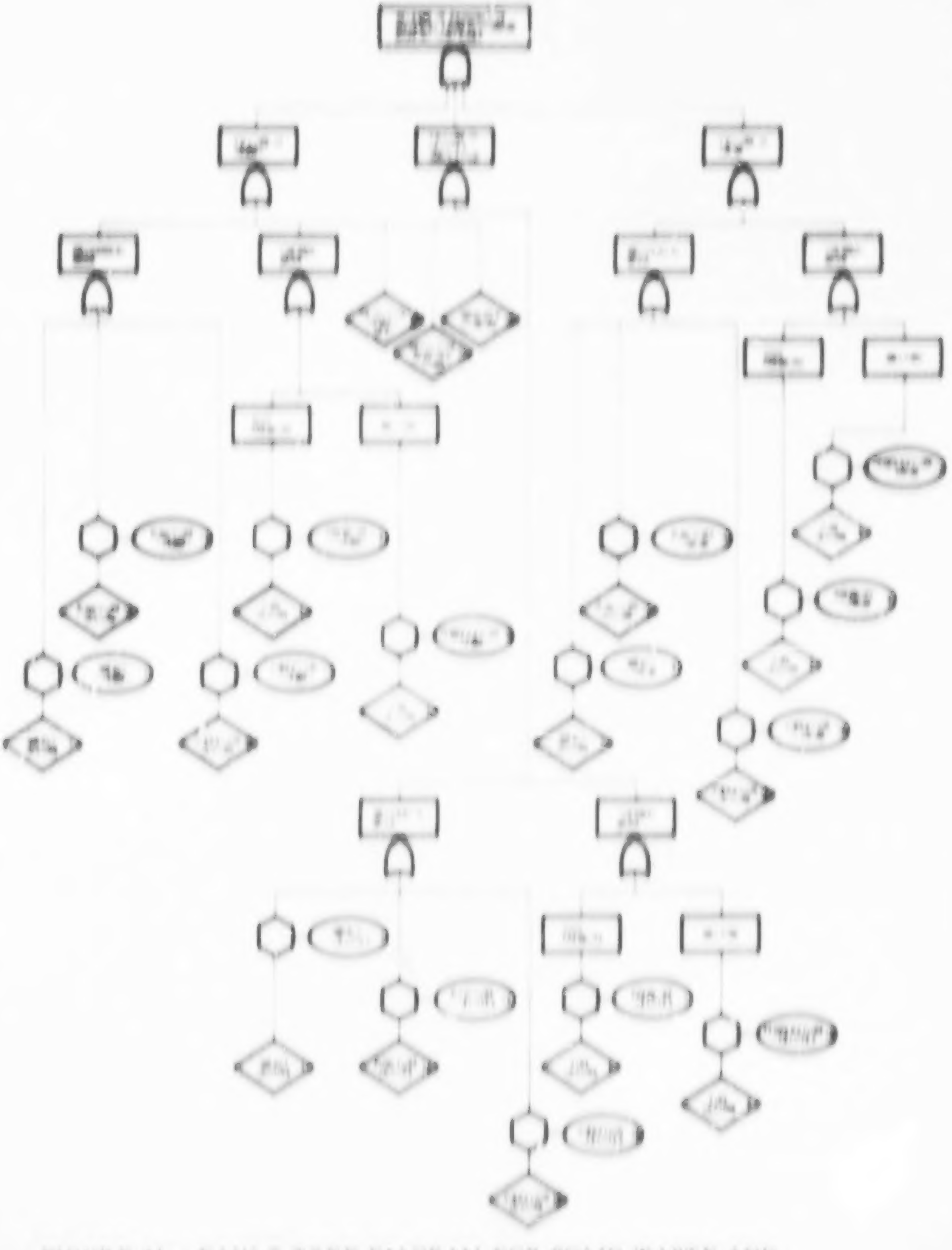

FIGURE 21. FAULT TREE DIAGRAM FOR SOLID WASTE AND NOBLE GAS SHIPPING CONTAINERS

TABLE [illegible]. FAULT TREE INPUT DATA FOR SPENT FUEL SHIPPING CONTAINER ON TRUCK[a]

No.	Mechanism	Input Event Name	Conditional Release Probability								
			Small Release			Medium Release			Large Release		
			Minor Accident	Moderate Accident	Severe Accident	Minor Accident	Moderate Accident	Severe Accident	Minor Accident	Moderate Accident	Severe Accident
1	Impact	Impact Cause[b]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
2		Impact - Cladding	[illegible]			[illegible]			[illegible]		
3		Impact - Inner Seal[c]	[illegible]			[illegible]			[illegible]		
4		Impact - Shield, Inner Seal[c]	[illegible]			[illegible]			[illegible]		
5		Impact - Closure Seal	[illegible]			[illegible]			[illegible]		
6	Thermal	Fire Cause[b]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
7		Pressure - Cladding	[illegible]			[illegible]			[illegible]		
8		Pressure - Inner Seal[c]	[illegible]			[illegible]			[illegible]		
9		Pressure - Shield, Inner Seal[c]	[illegible]			[illegible]			[illegible]		
10		Pressure - Closure Seal[c]	[illegible]			[illegible]			[illegible]		
11		Temperature - Cladding	[illegible]			[illegible]			[illegible]		
12		Temperature - Inner Seal	[illegible]			[illegible]			[illegible]		
13		Temperature - Shield, Inner Seal	[illegible]			[illegible]			[illegible]		
14		Temperature - Closure Seal	[illegible]			[illegible]			[illegible]		
15		Pressure - Excessive Setting of Pressure Relief Valve	[illegible]			[illegible]			[illegible]		
16	Puncture	Puncture Cause[b]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
17		Puncture - Inner Seal[c]	[illegible]								
18		Puncture - Shield, Inner Seal[c]	[illegible]								
19		Puncture - Closure Seal[c]	[illegible]								
20		Puncture - [illegible]	[illegible]								
21		[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
22	Vibration	Vibration Cause	[illegible]								
23		Vibration - Cladding	[illegible]			[illegible]			[illegible]		
24		Vibration - Inner Seal	[illegible]			[illegible]			[illegible]		
25		Vibration - Shield, Inner Seal	[illegible]			[illegible]			[illegible]		
26		Vibration - Closure Seal	[illegible]			[illegible]			[illegible]		
27	Equipment Defects	Defective Seal	[illegible]			[illegible]			[illegible]		
28	Human	Improper Loading	[illegible]			[illegible]			[illegible]		
29	Error	Improper Closure	[illegible]			[illegible]			[illegible]		

[a] [illegible]

[b] [illegible]

[c] [illegible]

TABLE 33. FAULT TREE INPUT DATA FOR SPENT FUEL SHIPPING CONTAINER BY RAIL[a]

			[illegible]								
			[illegible]			[illegible]			[illegible]		
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]		[illegible]	[illegible]			[illegible]			[illegible]		
[illegible]		[illegible]	[illegible]			[illegible]			[illegible]		
[illegible]		[illegible]	[illegible]			[illegible]			[illegible]		
[illegible]		[illegible]	[illegible]			[illegible]			[illegible]		
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]		[illegible]	[illegible]			[illegible]			[illegible]		
[illegible]		[illegible]	[illegible]			[illegible]			[illegible]		
[illegible]		[illegible]	[illegible]			[illegible]			[illegible]		
[illegible]		[illegible]	[illegible]			[illegible]			[illegible]		
[illegible]		[illegible]	[illegible]			[illegible]			[illegible]		
[illegible]		[illegible]	[illegible]			[illegible]			[illegible]		
[illegible]		[illegible]	[illegible]			[illegible]			[illegible]		
[illegible]		[illegible]	[illegible]			[illegible]			[illegible]		
[illegible]		[illegible] [illegible]	[illegible]			[illegible]			[illegible]		
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]		[illegible]	[illegible]			[illegible]			[illegible]		
[illegible]		[illegible]	[illegible]			[illegible]			[illegible]		
[illegible]		[illegible]	[illegible]			[illegible]			[illegible]		
[illegible]		[illegible]	[illegible]								
[illegible]		[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]								
[illegible]		[illegible]	[illegible]			[illegible]			[illegible]		
[illegible]		[illegible]	[illegible]			[illegible]			[illegible]		
[illegible]		[illegible]	[illegible]			[illegible]			[illegible]		
[illegible]		[illegible]	[illegible]			[illegible]			[illegible]		
[illegible]	[illegible] [illegible]	[illegible]	[illegible]			[illegible]			[illegible]		
[illegible]	[illegible]	[illegible]	[illegible]			[illegible]			[illegible]		
[illegible]	[illegible]	[illegible]	[illegible]			[illegible]			[illegible]		

[a] [illegible]

[illegible]	[illegible]
[illegible]	[illegible]
[illegible]	[illegible]
[illegible]	[illegible]
[illegible]	[illegible]

TABLE 34. FAULT TREE INPUT DATA FOR SPENT FUEL SHIPPING CONTAINER ON BARGE[a]

TABLE 15. FAULT TREE INPUT DATA FOR PLUTONIUM SHIPPING CONTAINER ON TRUCK*

No.	Mechanism	Input Event Name	Conditional Release Probability								
			Small Release			Medium Release			Large Release		
			Minor Accident	Moderate Accident	Severe Accident	Minor Accident	Moderate Accident	Severe Accident	Minor Accident	Moderate Accident	Severe Accident
[illegible]	Impact	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]		[illegible]	[illegible]			[illegible]			[illegible]		
[illegible]		[illegible]	[illegible]			[illegible]			[illegible]		
[illegible]		[illegible]	[illegible]			[illegible]			[illegible]		
[illegible]	Thermal	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]		[illegible]	[illegible]			[illegible]			[illegible]		
[illegible]		[illegible]	[illegible]			[illegible]			[illegible]		
[illegible]		[illegible]	[illegible]			[illegible]			[illegible]		
[illegible]		[illegible]	[illegible]			[illegible]			[illegible]		
[illegible]		[illegible]	[illegible]			[illegible]			[illegible]		
[illegible]		[illegible]	[illegible]			[illegible]			[illegible]		
[illegible]	Puncture	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]		[illegible]	[illegible]			[illegible]			[illegible]		
[illegible]		[illegible]	[illegible]			[illegible]			[illegible]		
[illegible]		[illegible]	[illegible]			[illegible]			[illegible]		
[illegible]	[illegible]	[illegible]	[illegible]			[illegible]			[illegible]		
[illegible]		[illegible]	[illegible]			[illegible]			[illegible]		
[illegible]		[illegible]	[illegible]			[illegible]			[illegible]		
[illegible]		[illegible]	[illegible]			[illegible]			[illegible]		
[illegible]	[illegible]	[illegible]	[illegible]			[illegible]			[illegible]		
[illegible]		[illegible]	[illegible]			[illegible]			[illegible]		
[illegible]	[illegible]	[illegible]	[illegible]			[illegible]			[illegible]		

[illegible]

[illegible]

[illegible]

TABLE 3. FAULT TREE INPUT DATA FOR PLUTONIUM SHIPPING CONTAINER ON RAIL[a]

No.	Mechanism	Input Event Name	Conditional Release Probability								
			Small Release			Medium Release			Large Release		
			Minor Accident	Moderate Accident	Severe Accident	Minor Accident	Moderate Accident	Severe Accident	Minor Accident	Moderate Accident	Severe Accident
1	Impact	Impact Occurs[b]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
2		Impact + Vessel[c]	[illegible]			[illegible]			[illegible]		
3		Impact + Container[c]	[illegible]			[illegible]			[illegible]		
4		Impact + Drum[c]	[illegible]			[illegible]			[illegible]		
5	Thermal	Fire Occurs[b]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
6		Pressure + Vessel[c]	[illegible]			[illegible]			[illegible]		
7		Pressure + Container[c]	[illegible]			[illegible]			[illegible]		
8		Pressure + Drum[c]	[illegible]			[illegible]			[illegible]		
9		Temperature + Vessel[c]	[illegible]			[illegible]			[illegible]		
10		Temperature + Container[c]	[illegible]			[illegible]			[illegible]		
11		Temperature + Drum[c]	[illegible]			[illegible]			[illegible]		
12	Puncture	Puncture Occurs[b]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
13		Puncture + Vessel[c]	[illegible]			[illegible]			[illegible]		
14		Puncture + Container[c]	[illegible]			[illegible]			[illegible]		
15		Puncture + Drum[c]	[illegible]			[illegible]			[illegible]		
16	Vibration	Vibration Occurs	[illegible]			[illegible]			[illegible]		
17		Vibration + Vessel[c]	[illegible]			[illegible]			[illegible]		
18		Vibration + Container[c]	[illegible]			[illegible]			[illegible]		
19		Vibration + Drum[c]	[illegible]			[illegible]			[illegible]		
20	Equipment Defects	Defective Vessel Seal	[illegible]			[illegible]			[illegible]		
21		Defective Penetrations	[illegible]			[illegible]			[illegible]		
22	Human Error	Improper Closure	[illegible]			[illegible]			[illegible]		

[a] Based on data and [illegible] in Table [illegible] with the following adjustments:

Event No.	Multiplier
2 - 4	[illegible]
6 - 11	[illegible]
13 - 15	[illegible]
17 - 19	[illegible]

TABLE 37. FAULT TREE INPUT DATA FOR SHIPPING CONTAINER OF HIGH LEVEL RADIOACTIVE SOLID WASTE OR NOBLE GAS ON TRUCK[a]

No.	Mechanism	Input Event Name	Conditional Release Probability								
			Small Release			Medium Release			Large Release		
			Minor Accident	Moderate Accident	Severe Accident	Minor Accident	Moderate Accident	Severe Accident	Minor Accident	Moderate Accident	Severe Accident
1	Impact	Impact Occurs	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
2		Impact → Can or Canister	[illegible]			[illegible]			[illegible]		
3		Impact → Cask	[illegible]			[illegible]			[illegible]		
4		Impact → Closure Seal	[illegible]			[illegible]			[illegible]		
5	Thermal	Fire Occurs	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
6		Pressure → Can or Canister	[illegible]			[illegible]			[illegible]		
7		Pressure → Cask	[illegible]			[illegible]			[illegible]		
8		Pressure → Closure Seal	[illegible]			[illegible]			[illegible]		
9		Temperature → Can or Canister	[illegible]			[illegible]			[illegible]		
10		Temperature → Cask	[illegible]			[illegible]			[illegible]		
11		Temperature → Closure Seal	[illegible]			[illegible]			[illegible]		
12	Puncture	Puncture Occurs	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
13		Puncture → Can or Canister	[illegible]			[illegible]			[illegible]		
14		Puncture → Cask	[illegible]			[illegible]			[illegible]		
15		Puncture → Closure Seal	[illegible]			[illegible]			[illegible]		
16		Puncture → Cooling System	[illegible]								
17		Content Leaks Out	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
18	Vibration	Vibration Occurs	[illegible]			[illegible]			[illegible]		
19		Vibration → Can or Canister	[illegible]			[illegible]			[illegible]		
20		Vibration → Cask	[illegible]			[illegible]			[illegible]		
21		Vibration → Closure Seal	[illegible]			[illegible]			[illegible]		
22	Equipment Defects	Defective Seal	[illegible]			[illegible]			[illegible]		
23	Human	Inadequate Cooling	[illegible]			[illegible]			[illegible]		
24	Error	Improper Closure	[illegible]			[illegible]			[illegible]		

[a] [illegible]

[b] [illegible]

[c] [illegible]

TABLE 16. FAULT TREE INPUT DATA FOR SHIPPING CONTAINER OF HIGH LEVEL RADIOACTIVE SOLID WASTE OR NOBLE GAS ON RAIL[a]

No.	Subsystem	Input Event Name	Conditional Release Probability								
			Small Release			Medium Release			Large Release		
			Minor Accident	Moderate Accident	Severe Accident	Minor Accident	Moderate Accident	Severe Accident	Minor Accident	Moderate Accident	Severe Accident
1	Impact	Impact Occurs	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
2		Impact → Gas or Canister	[illegible]			[illegible]			[illegible]		
3		Impact → Gasket	[illegible]			[illegible]			[illegible]		
4		Impact → Closure Seal	[illegible]			[illegible]			[illegible]		
5	Thermal	Fire Occurs	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
6		Pressure → Gas or Canister	[illegible]			[illegible]			[illegible]		
7		Pressure → Gasket	[illegible]			[illegible]			[illegible]		
8		Pressure → Closure Seal	[illegible]			[illegible]			[illegible]		
9		Temperature → Gas or Canister	[illegible]			[illegible]			[illegible]		
10		Temperature → Gasket	[illegible]			[illegible]			[illegible]		
11		Temperature → Closure Seal	[illegible]			[illegible]			[illegible]		
12	Puncture	Puncture Occurs	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
13		Puncture → Gas or Canister	[illegible]			[illegible]			[illegible]		
14		Puncture → Gasket	[illegible]			[illegible]			[illegible]		
15		Puncture → Closure Seal	[illegible]			[illegible]			[illegible]		
16		Puncture → Cooling System	1.0								
17		Coolant Leaks Out	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
18	Vibration	Vibration Occurs	[illegible]			[illegible]			[illegible]		
19		Vibration → Gas or Canister	[illegible]			[illegible]			[illegible]		
20		Vibration → Gasket	[illegible]			[illegible]			[illegible]		
21		Vibration → Closure Seal	[illegible]			[illegible]			[illegible]		
22	Equipment Defects	Defective Seal	[illegible]			[illegible]			[illegible]		
23	Human	Inadequate Closure	[illegible]			[illegible]			[illegible]		
24	Error	Improper Closure	[illegible]			[illegible]			[illegible]		

[a] Based on data and footnotes in Table [illegible] with the following adjustments:

Input Events	Multiplier
1-4	[illegible]
5-11	[illegible]
12-15	[illegible]
17-21	[illegible]

CALCULATIONS OF RELEASE PROBABILITIES

The logical relations and probability values in the fault tree descriptions of the shipping containers and transport vehicles under study have been programmed onto a computer. The probability that a particular sequence of events in an accident of given severity leads to a loss of containment, called the release probability in this report, is given by the appropriate combination of input probability values according to the rules of Boolean algebra. In particular, the probabilities for those sequences consisting of only a few events are calculated exactly in the program that was used. For sequences with a larger number of components, Monte Carlo simulation of statistical failure rates was used in the program to give the release probabilities. The simulations are carried out by examining the fault tree with randomly failed components in a large number of trials. An approximation to the release probability for each sequence is obtained from a count of the number of containment failures in the computer trials, from biasing factors, and from input data.

Failure Sequences

Selections from the complete set of calculations of failure sequences for each of the shipping containers are presented in Tables 39, 40, and 41. Only those sequences with probabilities greater than one percent of the largest value in each set are listed in the tables. The program computes many more sequences of lesser probability, but in all accident situations studied, no more than twenty sequences were required to include all sequences greater than one percent of the largest value.

In the case of a spent fuel cask, for example, the most probable sequence of events leading to a release is described in Table 39. The identification code of the component events of a fault tree in Table 39 is keyed to that of Table 32. An accident occurs in which the corrugated jacket containing the neutron shield water is punctured, causing the loss of the water. This is represented by Event 21, which in Table 39 is given the name "coolant leaks out" with a probability equal to that of Event 16, "puncture occurs." Loss of the neutron shield implies that heat from the spent fuel is not dissipated adequately. The resultant internal heat source raises the temperature of the cladding and the closure seal. Release of radioactive material from the shipping cask occurs only when both the cladding and the closure seal fail, according to Figure 19. These failure events are represented by the code numbers 11 and 14, respectively.

Summary of Release Probabilities

The conditional release probability is the fraction of accidents yielding release. This probability of release incorporates both the conditional

TABLE 39. SELECTED RELEASE SEQUENCES FOR SPENT FUEL SHIPPING CONTAINER[a]

	Conditional Release Probability					
	Truck					Rail
	Minor Accident	Moderate Accident		Severe Accident		Severe Accident
Sequence of Events	Small Release	Small Release	Medium Release	Medium Release	Large Release	Large Release
11 14 21	0.9×10^{-3}	0.1×10^{-2}	0.3×10^{-3}	0.6×10^{-5}	0.2×10^{-6}	0.5×10^{-6}
11 14 6 28	0.9×10^{-3}	0.1×10^{-2}	0.3×10^{-3}	0.6×10^{-5}	0.2×10^{-6}	0.5×10^{-6}
6 11 14	0.4×10^{-4}	0.6×10^{-3}	0.1×10^{-3}	0.8×10^{-6}	0.3×10^{-5}	0.3×10^{-6}
11 15 16 28	0.9×10^{-5}	0.1×10^{-4}	0.3×10^{-5}			0.5×10^{-6}
11 15 21	0.9×10^{-5}	0.1×10^{-4}	0.3×10^{-5}			0.5×10^{-6}
7 14 16 28	0.9×10^{-5}		0.3×10^{-5}			
7 14 21	0.9×10^{-5}	0.1×10^{-4}				0.5×10^{-6}
1 5 11 16 28		0.1×10^{-4}				
11 16 28 29			0.3×10^{-5}			
11 16 28 26			0.3×10^{-5}			
11 21 29			0.3×10^{-5}			
11 21 26			0.3×10^{-5}			
11 14 29				0.1×10^{-5}	0.5×10^{-7}	
6 11 15				0.9×10^{-6}	0.3×10^{-7}	
6 11 26				0.9×10^{-6}	0.7×10^{-6}	
6 11 29				0.9×10^{-6}	0.2×10^{-6}	
6 7 14				0.9×10^{-6}	0.3×10^{-7}	
11 14 26					0.5×10^{-7}	

[a] Probability values for certain release sequences that are less than one percent of the greatest probability value appearing in each column are not entered in the table.

TABLE 40. SELECTED RELEASE SEQUENCES FOR PLUTONIUM SHIPPING CONTAINER[a]

[illegible]

TABLE 41. SELECTED RELEASE SEQUENCES FOR HIGH LEVEL RADIOACTIVE SOLID WASTE OR NOBLE GAS SHIPPING CONTAINER[a]

	Conditional Release Probability					
	Rail					Truck
	Minor Accident	Moderate Accident		Severe Accident		Severe Accident
Sequence of Events	Small Release	Small Release	Medium Release	Medium Release	Large Release	Large Release
6 8 16	0.1x10-3	0.1x10-3	0.3x10-4	0.3x10-4	0.1x10-5	0.6x10-8
6 8 12	0.1x10-3	0.1x10-3		0.3x10-4		0.4x10-8
6 7 16	0.1x10-4	0.1x10-4	0.3x10-5		0.1x10-6	
6 12 15	0.6x10-5	0.6x10-5	0.2x10-5	0.2x10-5	0.6x10-7	
8 12 13	0.6x10-5	0.6x10-5	0.2x10-5	0.2x10-5	0.6x10-7	
6 11 16	0.2x10-5	0.2x10-5	0.6x10-6	0.6x10-6	0.3x10-7	
6 11 12	0.2x10-5	0.2x10-5	0.6x10-6	0.6x10-6	0.3x10-7	
5 6 8	0.1x10-5	0.1x10-4	0.3x10-5	0.2x10-4	0.7x10-6	0.8x10-7
1 4 6 12	0.1x10-5					0.1x10-8
1 4 6 16	0.1x10-5	0.1x10-5	0.4x10-6			
6 7 12	0.1x10-4				0.1x10-6	
5 6 7				0.2x10-6	0.7x10-7	
5 6 11				0.4x10-6	0.1x10-7	0.2x10-8
6 21						0.2x10-8
6 23						0.2x10-8
1 4 6 16						0.1x10-8
1 2 4						0.1x10-8

[a]Probability values for certain release sequences that are less than one percent of the greatest probability value appearing in each column are not entered in the table.

probability of an accident severity given an accident and the conditional probability of a container damage severity given an accident severity. The conditional release probabilities for spent fuel, recycled plutonium, noble gas and high level radioactive solid waste shipping containers have been calculated. Results are presented for a variety of accident conditions in Table 42.

The values in Table 42 amount to calculations of sensitivity of a basic failure probability data set to changes in accident conditions and to changes in the logical connections of the data. The release probabilities for plutonium and solid-waste containers are not significantly different. Compared to the spent fuel shipping container that was modeled, the plutonium and waste containers are calculated to be less likely to lose their contents. This comparison is largely related to the internal heat source in the spent fuel container that is lacking in the plutonium container and the higher probability assigned to fuel cladding failure than that assigned to waste can failure.

For the transportation scenario adopted in Section V, the fraction of accidents of given severity associated with damages of given severity is summarized in Table 43. On the average, these data indicate that about one percent of spent fuel accidents yield releases, and about 0.02 percent of accidents to other shipments yield releases.

The most severe cases that would involve the highest release, large damages in severe accidents, occur in about 0.01 percent of spent fuel accidents, about 4×10^{-7} of recycled plutonium accidents, and about 2×10^{-6} of accidents to high level radioactive solid waste shipments and noble gas shipments. The releases shown to be of greatest frequency for most material shipment accidents are those characterized by small damages in severe accidents.

TABLE 42. RELEASE PROBABILITIES FOR SHIPPING CONTAINERS

Shipping Container	Transport Mode	Release Severity	Conditional Release Probability			
			Minor Accident	Moderate Accident	Severe Accident	Average[a] Accident
Spent Fuel	Truck	Small	1.9E-3	3.2E-3	4.0E-4	2.1E-3
		Medium	4.7E-4	8.1E-4	1.0E-4	5.3E-4
		Large	2.1E-5	3.4E-5	4.4E-6	2.3E-5
	Rail	Small	9.8E-3	1.0E-2	1.3E-2	9.3E-3
		Medium	2.3E-3	2.7E-3	3.4E-3	2.3E-3
		Large	9.7E-5	1.1E-4	1.5E-4	9.8E-5
	Barge	Small	6.7E-6	4.0E-3	1.1E-2	5.5E-4
		Medium	1.7E-6	1.0E-3	2.7E-3	1.4E-4
		Large	4.3E-8	4.3E-5	1.2E-4	5.9E-6
Recycled Plutonium	Truck	Small	8.2E-5	1.5E-4	7.9E-5	9.4E-5
		Medium	8.1E-6	1.6E-5	9.7E-6	6.6E-6
		Large	6.0E-8	1.2E-7	7.2E-8	7.1E-8
	Rail	Small	3.0E-4	4.1E-4	8.5E-4	3.1E-4
		Medium	3.8E-5	5.0E-5	8.8E-5	3.9E-5
		Large	3.0E-7	3.9E-7	7.6E-7	3.1E-7
High Level Radioactive Solid Waste or Noble Gas	Truck	Small	5.9E-5	9.4E-5	1.8E-5	6.5E-5
		Medium	1.4E-5	2.4E-5	3.1E-6	1.6E-5
		Large	5.3E-7	2.2E-7	1.0E-7	4.7E-7
	Rail	Small	2.5E-4	3.0E-4	3.7E-4	2.5E-4
		Medium	3.9E-5	4.2E-5	9.0E-5	3.9E-5
		Large	2.6E-6	4.4E-7	2.6E-6	2.4E-6

[a] Accident severities are weighted for each transport mode as shown in Table 11.

TABLE 43. RELEASE PROBABILITY FOR ADOPTED TRANSPORTATION SCENARIO

Shipping Container	Release Severity	Conditional Release Probability			
		Minor Accident	Moderate Accident	Severe Accident	Average Accident
Spent[a] Fuel	Small	8E-3	9E-3	1E-2	8E-3
	Medium	2E-3	2E-3	3E-3	2E-3
	Large	8E-5	1E-4	1E-4	9E-5
Recycled[b] Plutonium	Small	2E-4	3E-4	5E-4	2E-4
	Medium	2E-5	3E-5	5E-5	2E-5
	Large	4E-7	3E-7	4E-7	2E-7
High Level Radioactive Solid Waste or Noble Gas[c]	Small	2E-4	2E-4	3E-4	2E-4
	Medium	3E-5	4E-5	7E-5	3E-5
	Large	2E-6	4E-7	2E-6	2E-6

[a] Distribution of transport modes assumed to be 10 percent trucks, 85 percent rails, and 5 percent barge-truck combinations (split 75 percent barges and 25 percent trucks).

[b] Distribution of transport modes assumed to be 50 percent trucks and 50 percent rails.

[c] Distribution of transport modes assumed to be 25 percent trucks and 75 percent rails.

SECTION VII

CONSEQUENCES OF RADIOACTIVITY RELEASES

INTRODUCTION

Among the consequences of a release of radioactivity from a nuclear transportation accident are: quantity of radioactivity released; population dose; and public health effects. The risk of a release from a shipment of radioactive material is the expected value of the consequences of the release.

In an accident leading to a release, only a fraction of the total cargo of radioactivity is assumed to be released. The severity of container damage directly determines the release fraction of the radioactive contents and thus, the quantity of radioactivity released to the environment.

The released radioactive material may expose the population through a variety of mechanisms:

1. Solid or liquid material spilled on the ground near the accident.

2. Gaseous or particulate material dispersed into the atmosphere.

3. Fallout of gaseous or particulate material dispersed into the atmosphere.

4. Contamination of potable water supplies or the food chain.

The population dose may be acquired by at least four important pathways:

1. External exposure.
2. Immersion in a radioactive cloud.
3. Inhalation from a radioactive cloud.
4. Ingestion through the food chain.

The population dose is thus dependent on the radioactivity, chemical, and physical properties of the shipment; the population distribution; and quantity of released material transported from the accident to the population.

Public health effects can be determined from the population doses and published information on the biological effects of ionizing radiation. The health response can include illness and fatalities from acute and long-term effects, somatic and genetic.

RELEASE FRACTIONS

In an accidental release of radioactivity from a shipment, not all the radioactive contents can be expected to leave the shipping container. Estimates of the amount of radioactivity that actually escapes from an accidently opened container depends on the nature of radioactivity under consideration. For the purposes of estimating the risk in a conservative manner, the release fractions for all accidents are estimated for large releases assuming easily dispersible materials. The values of the release fractions that are applicable to accidents leading to small and medium releases are estimated as fractions of the large values. The scenarios discussed below provide an upper limit estimate of the public risk from accidental releases from shipments of the materials under study.

Spent Fuel

In accidents involving spent fuel shipments, the most likely releases involve gaseous fission products or contaminants present in the cask coolant or leached through the surface of the fuel cladding (Reference 6). Fission gases tend to accumulate in the void space within the fuel rods during reactor operation and during the cooldown period after discharge from the reactor. Certain solid fission products diffuse from the fuel matrix and concentrate on the inner cladding surface. Upon cladding perforation, these products are available for release from the fuel element.

A possible source of contaminants in a release is the cask coolant to which fuel elements in the cask are exposed. In LWR spent fuel shipments, the coolant is taken from the water in the storage pool containing the fuel elements during the cooldown period. This situation occurs because the shipping cask is opened, loaded and closed while submerged in the storage pool water. Since some fuel elements incur cladding failures during reactor operation, some radioactive fission product contaminants naturally enter the water. These contaminants are available for release in the event of shipping cask failure.

One possible accident to a spent fuel shipment involves the heating and subsequent perforation or melting of the fuel cladding. Under these conditions, all the fission product gas accumulated in the void spaces and some of the other fission products are available for release. Negligible amounts of actinides, activation products, and corrosion products are assumed to be released in these circumstances (Reference 18). The quantity of fission products available for release is assumed to be 0.1 percent of the inventory in the fuel elements being carried. An independent estimate based on consideration of leaching processes in the outer thirty microns of the uranium oxide fuel used in LWRs and LMFBRs holds that no more than 0.01 percent of the fission product inventory is available for release. However, since no experimental confirmation exists for this number, the higher value is used. The solid fission products of greatest concern in the release are cesium and ruthenium, due to their relatively long half lives and because of their volatility.

The principal volatile fission products released from spent fuel are Kr-85 and I-131. Approximately thirty percent of the Kr-85 in the fuel element inventory is estimated (Reference 18) to migrate to the void space in the fuel element, and approximately two percent of the I-131 is estimated (Reference 18) to collect there.

Recycled Plutonium

Plutonium recycled from spent fuel to freshly fabricated fuel will likely be shipped from chemical processing plants to fabrication plants in oxide powder form. In this form, Pu can be economically mixed with natural uranium before being sintered into pellets that will be assembled into fuel elements. In an accident, the containment vessel lid can be broken or warped away from the vessel walls and some Pu powder released from the vessel, Celotex insulation, and drum. Since a release fraction is not available from the literature, a fraction of 0.1 percent is used typical of nonvolatile materials.

High Level Radioactive Solid Waste

A possible accident to a shipment of high level radioactive solidified waste would involve immediate loss of the cask cooling capability and the breakage or puncture of several of the waste canisters. The fraction of waste released in such an accident is complicated by the cooling requirement. If the waste melts, significant fractions of the cesium and ruthenium radionuclides may be released (Reference 19). Since a release fraction for such an accident is not known, a value of 0.5 percent is arbitrarily chosen as the release fraction for mixed fission products.

Noble Gas

Of the gaseous fission products, only Kr-85 is generated in sufficiently large quantities and has sufficiently long half life to merit consideration for separation from spent fuel elements, accumulation, and transportation from the chemical processing plants to the Federal Waste Repository. This gas would probably be shipped in standard cylinders pressurized to 2200 psig. In a credible accident, any loss of containment will mean a total release of the gas in a shipment.

When one of the gas cylinders is breached and the cask is breached, all the gas from that cylinder will eventually be lost from the shipment. However, not all the cylinders of a shipment necessarily lose their containment property in an accident. The concept of release fraction is restricted to refer only to the number of damaged cylinders in the case of noble gas accidents, whereas its meaning in the case of other shipments encompasses not only the number of damaged containers within a single shipment, but also the released fraction of the contents of a single container. Since a noble gas shipment carries an integral number of cylinders by hypothesis, the release fraction in accidents leading to releases less severe than a large release must be smaller by an integral number of cylinders. In particular, a small release fraction can be no smaller than one-sixth of the shipment.

Summary of Release Fractions

Release fractions in transportation accidents by material and severity are summarized in Table 44. The table also lists the release fraction averaged by transportation mode.

DISPERSION OF RADIOACTIVITY

Accidental releases of radioactivity from shipments may endanger the population through a variety of mechanisms. Releases from spent fuel, plutonium, and solidified waste shipments might contain solid material that spills onto the ground and provides a ground deposit source of external radiation. The most serious example of such a release is for part or all of a spent fuel element to exit its shipping cask. Such releases have been discussed elsewhere (Reference 18), and will not be considered further in this report.

In all the shipment accidents under consideration, the primary source of radiation exposure is assumed to result from atmospheric dispersion. Radionuclides may leave the shipping containers as gases or particles small enough to be transported through the atmosphere. These constitute clouds of airborne sources of external radiation. Only part of the solid material spilled from the container will be dispersed away from the scene of the accident by the atmosphere, since some particles of the solid material may be too large or too dense for airborne transport. The release fractions used in this report (Table 44) apply to releases of easily dispersible material.

TABLE 46. RELEASE FRACTIONS IN TRANSPORTATION ACCIDENTS

Material Transported	Released Radionuclide	Release Fraction			
		Large Release	Medium[b] Release	Small[c] Release	Average[d] Release
Spent Fuel	Kr-85	0.30[a]	0.15	0.003	0.054
	I-131	0.02[a]	0.01	0.0002	0.0023
	Fission Products	0.001	0.0005	0.00001	0.00011
Recycled Plutonium	Pu	0.001	0.0005	0.00001	0.000054
High-Level Solid Waste	Fission Products	0.005	0.0025	0.00005	0.00049
Noble Gas	Kr-85	1.0	0.5	0.17	0.23

[a] Reference 18.

[b] Assumed to be one-half the value for large releases.

[c] Assumed to be one percent the value for large releases.

[d] Weighted for each release severity for the transportation scenario adopted (Table 43).

The public may also absorb radiation by means other than external radiation sources. Some of the radioactive particles transported from the scene of a transportation accident to positions occupied by the public may become sources of radiation inside human bodies through the pathways of inhalation, ingestion, or open wounds. Of the possible internal pathways, only the inhalation pathway will be considered in this report. Plutonium is assumed to be insoluble.

Atmospheric Dispersion Model

In this study, the standard Gaussian plume diffusion model (Reference 20) was used to compute atmospheric transport of radioactivity. In this model, possible kinds of weather are characterized by seven Pasquill stability categories, A through G, with associated weather probabilities and average wind speeds. Published calculations (Reference 18) were used to simplify the computations. In every case, it was assumed that the radioactive material is released in a very short period of time at ground level.

For worst case assumption in nuclear safety analysis, it is common to use very conservative dispersion coefficients corresponding to Pasquill Type F, moderately stable meteorological conditions. For this study, the more realistic assumption of average weather conditions was used. The average value lies between Pasquill Types D and F. For some calculations, the weather condition occurring with the greatest probability, Pasquill Type D, was used. Pasquill Type G stability category was not used because of its low frequency, short duration, and calm wind conditions.

Dose Coefficients

The meteorological diffusion model calculates the concentration at a receptor on the ground as a function of distance, direction and time from radioactivity released in a very short period of time at ground level. The exposure to the receptor is expressed in terms of the integrated concentration resulting from the passage of the airborne cloud of radioactivity. The dose coefficient is the factor which transforms the integrated concentration of radioactivity at the receptor position into a dose absorbed by the receptor.

The dose coefficient for external radiation sources depends on the energy of the radiation under consideration, the energy absorption coefficient of the absorbing medium, the scattering properties of the absorbing medium and the geometry of the emitter-receptor situation. The coefficient for internal radiation sources must also include the mass of the critical organ under consideration, information on intake, retention, distribution, translocation, and the radioactive decay rate of the radionuclide under consideration. Dose coefficients are given in Table 45 for several critical organs for radionuclides in the four materials undergoing transportation.

TABLE 45. DOSE COEFFICIENTS

Material Transported	Nuclide	Dose Coefficient $\left(\frac{rem \cdot m^3}{Ci \cdot sec}\right)$			
		Whole Body	Lung	Gastrointestinal Tract	Thyroid
Spent Fuel	Kr-85	1.8E-1[a]			
	I-131				4.76E2[c] 1.48E2[d]
	Fission Products	1.8E-1[a]	1.6E2[b]	1.6E1[b]	
Recycled Plutonium	Pu 238-242		1.2E4[b]		
High-Level Radioactive Solid Waste	Fission Products	1.8E-1[a]	1.6E2[c]	7.0E0[b]	
Noble Gas	Kr-85	1.8E-1[a]			

[a] Reference 20
[b] Reference 6
[c] Reference 18 - Child
[d] Reference 18 - Adult

Individual Doses

In evaluating the consequences of radioactivity released from transportation accidents, it is necessary to calculate the dose that an individual might receive. The dose at a receptor on the ground varies with the distance from the release point in exponential fashion. The radioactive material is distributed downwind from a release such that the isopleths (contour lines of equal dose) are cigar shaped. The dose from an accident can be estimated by assuming a ground level release under average weather conditions and calculating the exposure dose delivered along the centerline of that pattern, i.e., the direction in which the highest exposures would occur.

The average dose in all directions from the accident, will be significantly less than the centerline dose. For average weather conditions, this is about five percent of the centerline dose at 50 meters (Reference 18).

Population Dose

The population dose resulting from radioactivity released from a transportation accident depends on both the spatial distribution of the dose and the number of persons exposed. The spatial distribution of the dose was estimated from published data (Reference 18) for Pasquill Type D, the most probable weather condition. The population dose is calculated by an approximate integration of the spatial dose and the population density in the vicinity of the accident.

The population density varies widely along the route of a shipment. Most facilities in the nuclear fuel cycle are located remote from population centers. Nuclear power plants, however, will be located nearer to urban centers. The probability distribution of the population density within 50 miles of presently operating reactors has been described (Reference 18) for the 1980 time period. The average population density near power plants is about three times the national average and is stated to be probably typical of the Eastern United States. About 75% of the area in a 50-mile radius is greater than the average United States population density; about 20% is greater than ten times; and about one percent is greater than 100 times.

The average distances of shipments in the nuclear power industry postulated in Section V of this report range from 410 miles for spent fuel in 2000 to 2,175 miles for radioactive wastes in 1975. Spent fuel and plutonium shipments, with an average shipping distance of 500 miles, predominate the transportation picture during the entire period. If accidents were presumed to occur randomly along the route, the population density distribution near nuclear power plants would be applicable to about ten percent of the route. The balance of the population density is assumed to be a distribution typical of the whole United States. About 15% of the land area has greater than the average United States population density; about ten percent of the area greater than three times; about one percent greater than 20 times; and about 0.1 percent greater than 100 times. The population model is summarized in Table 46. The probability distribution of the average population density in the vicinity of an accident as multiples of the national average density is assumed to apply to all shipments and all times studied in this report.

TABLE 46. AVERAGE POPULATION DENSITY

Multiple of the National Average Population Density	Probability
<1	0.6[illegible]
1- 5	0.2[illegible]
5- 10	0.080
10- 50	0.010
50-100	0.009
>100	0.001

An estimate of the population dose within a reasonably large area of an accident is facilitated by zoning the area according to population distribution. For an average accident site, the wind direction and population distribution are assumed to be independent and thus, the zones are assumed to be circular areas. No one will ordinarily be located within the zone containing the wrecked cargo. Some individuals may happen to enter this zone, which is assumed to extend radially from the accident to form a circle with an outer radius of about 500 feet. A uniform density of population (Table 1) is assumed to exist in the rest of the area, which is assumed to extend radially from the accident to form a circle of area 10^3 mi^2. The outer radius of this assumed population environment is thus about 18 mi.

HEALTH EFFECTS OF RADIATION EXPOSURE

The health effects of radiation exposure may be fatalities or illnesses. Acute effects (short term) are estimated from individual doses in rem and delayed effects (long term) are estimated from population doses in person-rem. The delayed effects may be somatic (cancer) or genetic. The basis for the effects used in this study is a recent review (Reference 51) of the biological effects of ionizing radiation.

Acute Effects

The doses at which various acute health effects occur exhibit statistical variation due to differences in the exposed population such as age, sex, health and other variables. The average dose which is lethal to 50% of an exposed population within 60 days after exposure is called the $LD_{50/60}$ dose. The $LD_{50/60}$ for human population has been estimated (Reference 22) to be about 300 rem. For other levels of exposure, the probability of death is a function of the dose. The acute lethal effects of whole body radiation exposure assumed for this study are summarized in Table 47.

TABLE 47. ACUTE EFFECTS OF RADIATION EXPOSURE[a]

Critical Organ	Dose Range (rem)	Fraction of Exposed Population	
		Fatalities	Nonfatal Effects
Whole Body	0- 50	0.00	0.00
	50- 200	0.25	0.50
	200- 300	0.50	1.00
	300- 500	0.75	1.00
	> 500	1.00	1.00
Specific Organs[b]	0- 500	0.00	0.00
	500-2000	0.25	0.50
	2000-3000	0.50	1.00
	3000-5000	0.75	1.00
	> 5000	1.00	1.00

[a] Reference 21.

[b] Lung, GI tract, and thyroid.

Similar considerations apply to acute nonfatal health effects. A variety of symptoms, including anorexia, nausea, fatigue, vomiting, and diarrhea, occur at different times after exposure and at different doses. These have been estimated in the literature (Reference 22) to occur to 50% of an exposed population in the range of 100 to 300 rem. The acute nonlethal effects of whole-body radiation exposure assumed for this study are summarized in Table 47.

In addition to the effects which occur when the whole body is exposed, similar types of effects occur when specific organs or tissues are irradiated as a result of inhalation of airborne radionuclides. The specific organs and tissues evaluated in this study are the lungs, GI tract, and thyroid. Although beta doses to the skin were calculated, the worst case result was well below the subacute effect reported in the literature for skin exposure and are thus considered to be of secondary importance. In general, the doses necessary to produce the same type of effects of whole body irradiation are considerably greater. For the purposes of this study, it was assumed that these organs are one-tenth as sensitive as for whole body exposure, i.e., to obtain the same effects would require ten times the exposure. The acute effects of radiation exposure to the specific organs and tissues assumed for this study are shown in Table 47.

Delayed Somatic and Genetic Effects

Long term health effects are based on the total population dose after excluding acute fatalities. The only somatic effect that needs to be taken into account is cancer induction (Reference 21). The excess mortality from all forms of cancer following whole body irradiation corresponds roughly to 50-165 deaths per million persons per rem during 25-27 years after irradiation (Reference 21). The fatalities from all forms of cancer resulting from whole body irradiation assumed for this study is 200 deaths per million person-rem. The model used is a conservative one of a linear relation with no threshold or repair mechanisms taken into account. The incidence of cancer lethality for whole body irradiation and to the specific organs and tissues assumed in this study are shown in Table 48.

According to data from the American Cancer Society, approximately one-third of all cancers respond to treatment. Consequently, the delayed nonfatal health effects for this study are assumed to be one-half of the cancer fatalities due to irradiation of the whole body, lung and GI tract. The total incidence of cancer to the thyroid is assumed to be amenable to treatment and thus constitutes a delayed nonfatal health effect. The delayed effects of radiation exposure assumed for this study are summarized in Table 48.

The genetic effects of radiation exposure were not explicitly evaluated in this study. Based on data in Reference 21, the genetic effects are approximately equal to those arising from the delayed somatic effects of whole body irradiation, i.e., 200 genetic defects per million person-rem.

TABLE 48. DELAYED SOMATIC EFFECTS OF RADIATION EXPOSURE[a]

Critical Organ	Incidence of Cancer (per 10^6 person-rem)	
	Fatalities	Nonfatal Effects
Whole Body	200	100
Lung	50	25
GI Tract	10	15
Thyroid		
Child		15
Adult		5

[a] Reference 21

SECTION VIII

RISKS FROM TRANSPORTATION ACCIDENTS

INTRODUCTION

The risk to the public from transportation accidents to shipments of radioactive material from the nuclear power industry takes into account both the magnitude or value of the consequences of the accidents and their frequency of occurrence. Three types of consequences have been analyzed in this study: the quantity of radioactivity released; the radiation doses resulting from the releases; and the public health effects of the radiation exposures. Since many events can lead to the same consequence, risk is defined by the average or expected value of the consequences of release, i.e., the probability weighted sum of all values of a consequence. Risks are projected for the next fifty years.

The estimates of risks to follow begin with transportation accidents: the frequency of accidents and the frequency of radiological releases. A scenario is postulated in which a hypothetical individual is exposed to a release from a transportation accident at a distance of 0.1 mile. The exposures are presented as annual averages, i.e., averaged over the variety of transportation modes, accident severities and package damage severities, and as worst cases for accidents which occur very infrequently. This is followed by the calculation of population doses. The individual health risks are calculated as the acute effect based on the assumed scenario for the average exposure and the worst case expected effect. Long term health effects, fatal and nonfatal, are calculated based on the total population dose. Finally, the risks from transportation accidents in the nuclear power industry are compared to other sources of radiation exposure.

ACCIDENT FREQUENCY

The frequency of accidents was expressed in Section VI (Table 28) as the number of accidents occurring in a million shipment-miles of transportation activity. The transportation scenarios given in Section V and the projections given for the annual shipment-miles for transportation of spent fuel (Table 12), recycled plutonium (Table 19), high level radioactive solid waste (Table 24) and noble gas (Table 27), were used to calculate the frequency of transportation accidents from 1975 to 2020. The average number of accidents per year and the average time between accidents are presented in Figure 22.

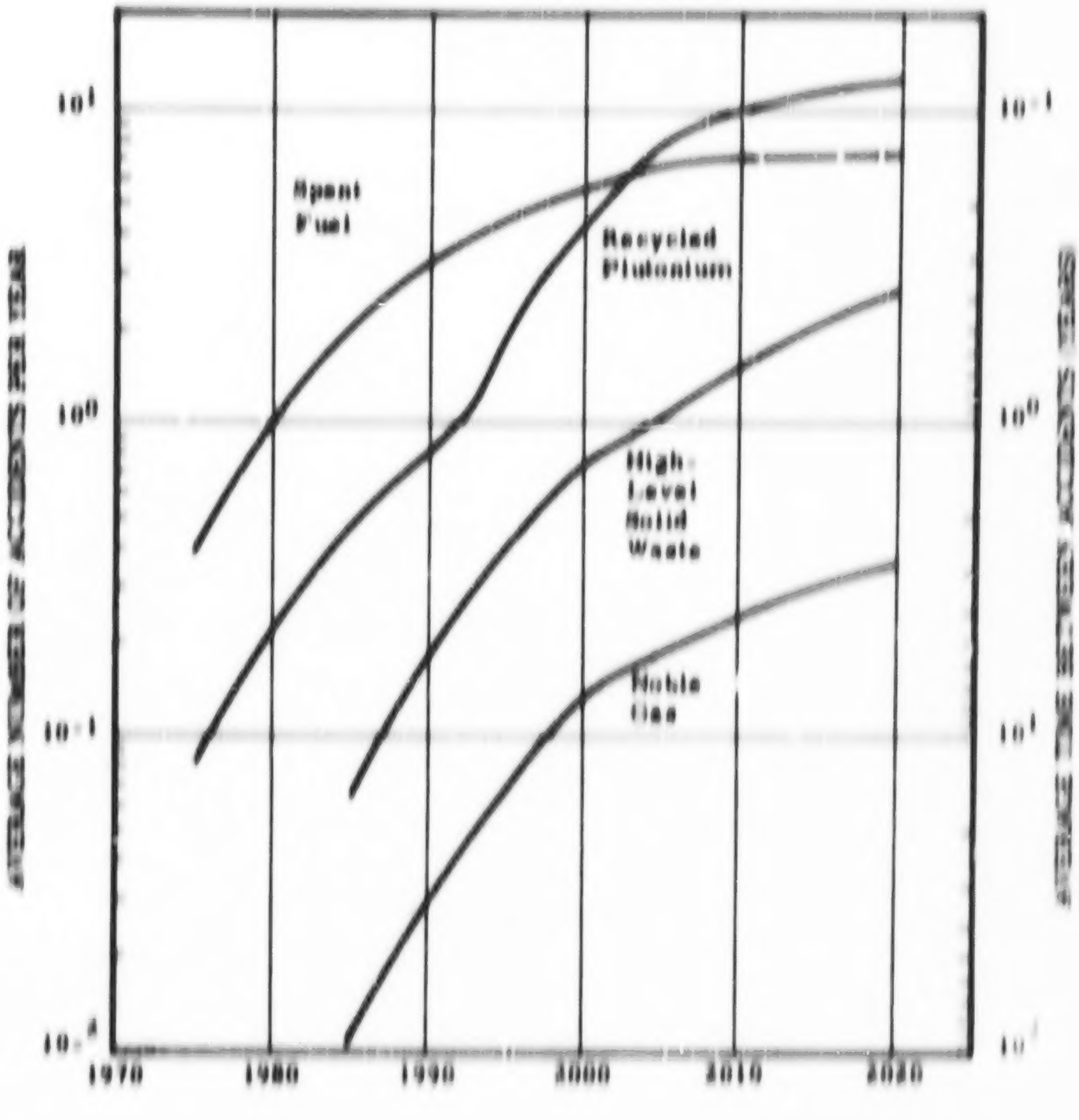

FIGURE 22. FREQUENCY OF TRANSPORTATION ACCIDENTS

The total accident frequency is less than one per year in 1975, exceeds one per month after 2000 and reaches two per month in 2020. Shipments of spent fuel dominate the accident picture until about the year 2000. The approximate accident rate for spent fuel transportation ranges from one accident per 900 shipments in 1975 to one accident per 2000 shipments in 2020. This reduction is due entirely to the reduction in shipping distances during the period. The annual shipments of plutonium exceed the annual shipments of spent fuel after 2005 because of the rapid growth of the LMFBR. By 2020, the average number of accidents to shipments of recycled plutonium exceeds one per month. The approximate accident rate for plutonium transportation ranges from one accident per 700 shipments in 1975 to one accident per 1700 shipments in 2020. The accident rates for high-level solid waste and noble gas transportation are approximately one accident per 500 shipments for the entire period.

It is important to note that in the overwhelming majority of cases, these accidents will not result in the release of radioactivity. As indicated in Table 43, only about one percent of the spent fuel accidents result in releases and about 0.02 percent of the accidents involving other materials result in releases. The effect of the release probability (for the transportation scenario adopted) on the frequency of transportation accident releases is shown in Figure 41. Also shown is the average time between releases.

Releases from accidents involving spent fuel totally dominate the release frequency. The release frequency ranges from approximately one release per 250 years in 1975 to one release per 11 years in 2020. The approximate release rate for spent fuel ranges from one release per 90,000 shipments in 1975 to one release per 400,000 shipments in 2020. The average release rate for plutonium is approximately one release per 5,000,000 shipments. The release rates for high-level solid waste and noble gas are approximately one release per 2,000,000 shipments for the entire period.

The release fractions tabulated in Section VII (Table 44) were combined with the transportation data in Section V and the release probabilities in Section VI (Table 43) to calculate the amount of radioactivity released from transportation activity in the nuclear power industry from 1975 to 2020. The results were averaged by mode, accident severity, release probability and package damage severity. The average annual release of radioactivity is summarized in Table 49. The largest average releases of radioactivity occur from spent fuel.

The averaging process distributes the releases over all shipments; however, only a small fraction of all shipments is associated with releases. The

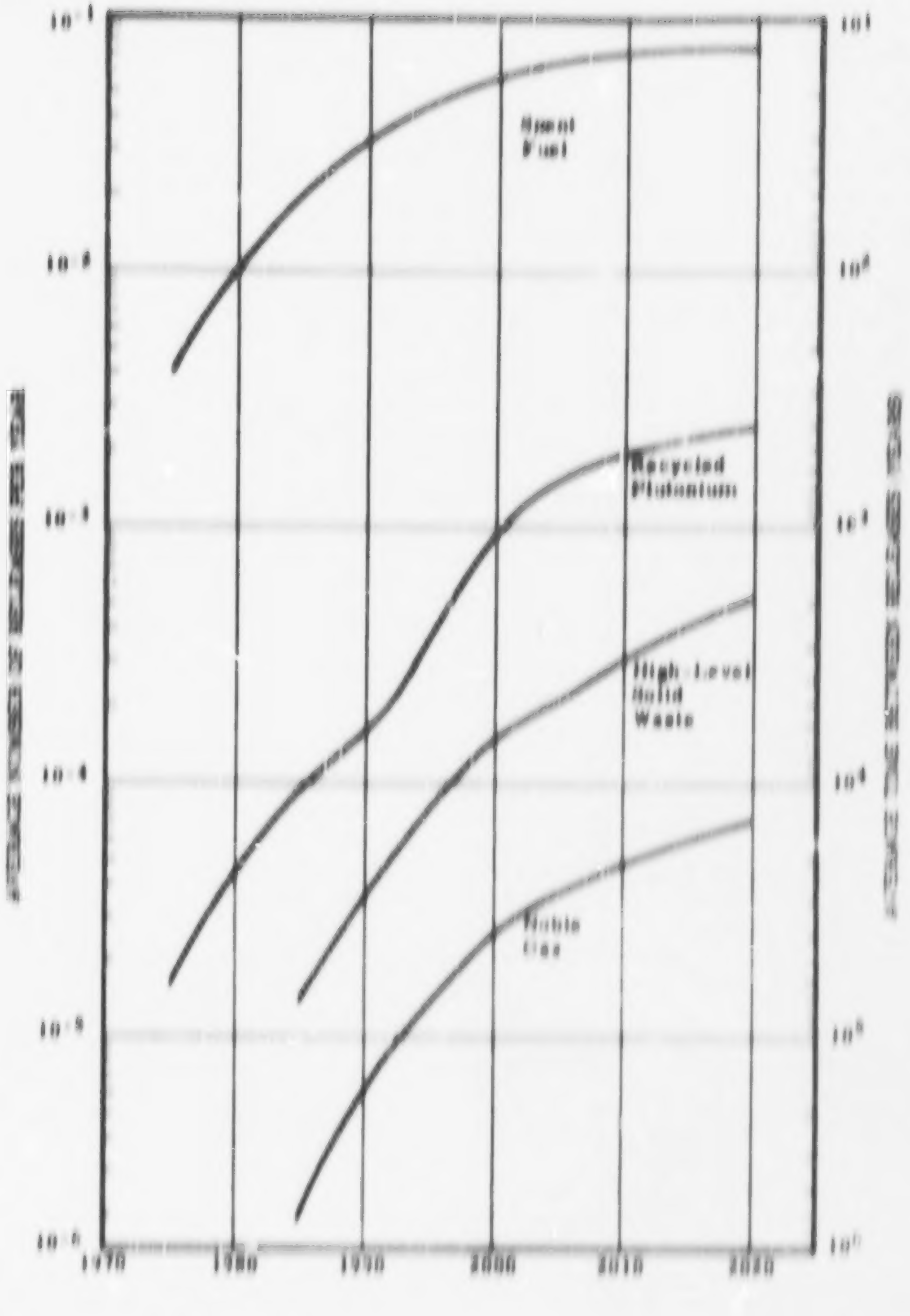

FIGURE 21. FREQUENCY OF TRANSPORTATION ACCIDENT RELEASES

TABLE 49. AVERAGE ANNUAL RELEASE OF RADIOACTIVITY

Year	Average Annual Release (Ci)					
	Spent Fuel					
	Kr-85	I-131	Fission Product	Plutonium	High-Level Radioactive Solid Waste	Noble Gas
1975	5.5E-1	7.4E-6	1.6E-1	3.5E-4		
1980	1.4E0	2.8E-5	4.6E-1	9.5E-4		
1985	2.9E0	3.7E-5	9.3E-1	2.1E-3	6.5E-3	2.7E-1
1990	5.7E0	4.4E-4	1.4E0	2.9E-3	1.7E-2	7.6E-1
1995	8.8E0	2.7E-3	2.2E0	4.4E-3	3.7E-2	1.8E0
2000	1.0E1	8.9E-3	3.4E0	7.4E-3	6.7E-2	3.8E0
2005	1.2E1	1.7E-2	4.4E0	1.1E-2	8.6E-2	5.4E0
2010	1.3E1	2.2E-2	5.5E0	1.4E-2	1.2E-1	7.6E0
2015	1.3E1	2.7E-2	5.9E0	1.6E-2	1.4E-1	1.0E1
2020	1.3E1	3.1E-2	6.3E0	1.7E-2	1.4E-1	1.1E1

actual release occurs very infrequently as indicated in Figure 33. When it occurs, it will be larger than the average values shown in Table 49.

The average release fractions in Table 44 were applied to typical actual shipments. Because the transportation scenario is assumed constant over the entire period under study, the variation in radioactivity transported per shipment is small and due only to the nuclear reactor mix postulated in Section V. Consequently, the typical actual releases are relatively constant from 1975 to 2020.

A typical actual release from an accident involving spent fuel (SF) would be about 1000 curies of Kr-85, one curie of I-131 and 400 curies of mixed fission products (FP). A typical actual release from a plutonium shipment accident would be about 10 curies and from high-level radioactive solid waste (HSW) about 2000 curies. As discussed in Section VII, the smallest actual release from a noble gas (NG) shipment can be no less than the contents of one gas cylinder. This corresponds to about 400,000 curies of Kr-85. The average frequency of these actual releases is presented in Figure 33.

INDIVIDUAL EXPOSURES

The meteorological information discussed in Section VII was used to calculate the average dose to a hypothetical individual exposed on the centerline downwind from an average ground level release from a transportation accident at a distance of 0.1 mile under average weather conditions (Reference 18). The calculations were based on average annual releases from 1975 to 2020 shown in Table 49 and the dose coefficients given in Table 45. The results are presented in Table 50.

A more realistic calculation, however, would calculate conditional individual doses from infrequently occurring actual releases corresponding to the frequencies shown in Figure 33. The conditional dose was estimated for a ground level release under average weather conditions at a distance of 0.1 mile on the centerline of the exposure pattern. The results are shown in Table 51. The average conditional dose to all persons in all directions from the accident would be about one percent of the centerline dose at 0.1 mile for average weather conditions.

Comparison of the results between Tables 50 and 51 show conditional doses from actual releases significantly larger than average doses. Conditional doses from spent fuel releases are less than conditional doses from high-level solid wastes releases. Since spent fuel releases occur much more frequently (Figure 33) than high-level solid waste releases, the average annual doses from spent fuel accidents are greater than the average annual

TABLE 50. AVERAGE ANNUAL INDIVIDUAL DOSES AT 0.1 MILE

Year	Material	Critical Organ Dose (rem)					
		Kr-85 Whole Body	Fission Products and Pu			I-131 Thyroid	
			Whole Body	Lung	GI Tract	Adult	Child
1975	SF	7.5E-5	2.2E-5	2.9E-2	3.9E-3	4.0E-6	2.7E-6
	Pu			4.0E-3			
1980	SF	1.9E-4	6.1E-5	8.4E-2	8.4E-3	1.1E-5	7.2E-6
	Pu			1.1E-2			
1985	SF	4.0E-4	1.3E-4	1.7E-1	1.7E-2	2.0E-5	1.3E-5
	Pu			2.9E-2			
	HLW		8.9E-7	1.2E-3	5.2E-5		
	NG	3.0E-5					
1990	SF	7.8E-4	1.9E-4	2.6E-1	2.6E-2	2.4E-4	1.6E-4
	Pu			4.0E-2			
	HLW		2.1E-6	3.1E-3	1.4E-4		
	NG	1.0E-4					
1995	SF	1.2E-3	3.0E-4	4.0E-1	4.0E-2	1.9E-5	9.0E-6
	Pu			6.0E-2			
	HLW		5.1E-6	6.7E-3	3.0E-4		
	NG	2.5E-4					
2000	SF	1.4E-3	4.6E-4	6.2E-1	6.2E-2	4.0E-5	3.2E-5
	Pu			1.0E-1			
	HLW		9.2E-6	1.2E-2	5.1E-4		
	NG	5.4E-4					
2005	SF	1.6E-3	6.0E-4	8.0E-1	8.0E-2	9.2E-5	6.2E-5
	Pu			1.5E-1			
	HLW		1.2E-5	1.6E-2	6.9E-4		
	NG	7.6E-4					
2010	SF	1.8E-3	7.5E-4	1.0E0	1.0E-1	1.2E-4	8.0E-5
	Pu			1.9E-1			
	HLW		1.6E-5	2.2E-2	9.6E-4		
	NG	1.0E-3					
2015	SF	1.8E-3	8.1E-4	1.1E0	1.1E-1	1.5E-4	9.8E-5
	Pu			2.4E-1			
	HLW		2.2E-5	2.9E-2	1.3E-3		
	NG	1.4E-3					
2020	SF	1.8E-3	8.6E-4	1.1E0	1.1E-1	1.7E-4	1.1E-4
	Pu			2.3E-1			
	HLW		2.6E-5	3.5E-2	1.5E-3		
	NG	1.6E-3					

TABLE 51. CONDITIONAL INDIVIDUAL DOSES AT 0.1 MILE

Year	Material	Critical Organ Dose (rem)						
		Kr-85 Whole Body	Fission Products and Pu			I-131 Thyroid	
			Whole Body	Lung	GI Tract	Adult	Child
1975	SF	1.3E-1	3.4E-2	4.6E1	4.6E0	3.6E-3	1.3E-3
	Pu			2.9E2			
1980	SF	1.5E-1	3.6E-2	4.7E1	4.7E0	3.8E-3	1.4E-3
	Pu			2.9E2			
1985	SF	1.5E-1	3.7E-2	4.9E1	4.9E0	3.6E-3	1.3E-3
	Pu			2.7E2			
	HSW		3.6E-1	4.7E2	2.1E1		
	NG	3.0E1					
1990	SF	1.6E-1	3.6E-2	4.7E1	4.7E0	2.6E-2	9.8E-3
	Pu			2.8E2			
	HSW		3.9E-1	4.6E2	2.0E1		
	NG	3.0E1					
1995	SF	1.8E-1	4.0E-2	5.3E1	5.3E0	1.2E-1	4.3E-2
	Pu			1.0E2			
	HSW		3.4E-1	4.6E2	2.0E1		
	NG	3.0E1					
2000	SF	1.6E-1	4.8E-2	6.4E1	6.4E0	2.9E-1	1.1E-1
	Pu			1.1E2			
	HSW		3.1E-1	4.4E2	1.9E1		
	NG	3.0E1					
2005	SF	1.6E-1	5.1E-2	7.1E1	7.1E0	4.6E-1	1.7E-1
	Pu			9.1E1			
	HSW		3.1E-1	4.4E2	1.9E1		
	NG	3.0E1					
2010	SF	1.6E-1	6.1E-2	8.4E1	8.4E0	5.8E-1	2.2E-1
	Pu			8.7E1			
	HSW		3.1E-1	4.2E2	1.8E1		
	NG	3.0E1					
2015	SF	1.6E-1	6.6E-2	8.8E1	8.8E0	7.2E-1	2.7E-1
	Pu			8.3E1			
	HSW		2.9E-1	3.8E2	1.7E1		
	NG	3.0E1					
2020	SF	1.6E-1	7.0E-2	9.3E1	9.3E0	8.1E-1	3.0E-1
	Pu			8.4E1			
	HSW		2.7E-1	3.6E2	1.6E1		
	NG	3.0E1					

doses from high-level solid waste accidents. The average annual doses from Kr-85 released from noble gas accidents are much smaller than the average annual doses from Kr-85 released in spent fuel accidents. Although the release frequency from noble gas shipments is very low, the conditional releases are many times larger than the conditional releases of Kr-85 from spent fuel and thus the actual dose, when it occurs, is significantly larger.

For comparison purposes, the worst-case releases in 2020 and their expected frequencies of occurrence were calculated for large container sizes in severe accidents with large release fractions. The results are shown in Table 52. As expected, the releases and doses are significantly greater than those in Table 51. These worst-case releases are approximately three to four orders of magnitude less probable than the conditional values shown in Table 51.

POPULATION DOSES

The population dose was calculated by the method described in Section VII. The results are presented in Figures 24 through 27 for whole body, lung, GI tract and thyroid doses, respectively, from 1975 to 2020. Spent fuel exposures dominate the population doses in every category of exposure for the entire period.

The annual population dose from transportation accidents in the nuclear power industry can be compared with the annual doses received by the population from natural and man-made radiation sources. The expected value of the total annual whole body population dose from accidents in the nuclear power industry in 2020 is less than 10 [illegible] person-rem per year. The routine exposure of the population from environmental sources such as cosmic rays and natural radioisotopes in the earth's crust averages about 0.130 rem per year in the coterminous United States. The principal source of man-made radiation exposure has been from medical use of diagnostic x-rays averaging 0.1 rem per person per year. The total estimated annual population dose in the United States would be about 60 x 10^6 person-rem per year in 2020. The average annual transportation accident population dose is thus a very insignificant fraction of the total annual population dose received from natural background and from other man-made radiation sources.

The population doses shown in Figures 24 through 27 assume the uniform population density of the United States presented in Table 1. The population density distribution of Table 46, however, indicated that 15 percent of the coterminous United States has a population density greater than average. If an accident were to occur in an area where the population density is

TABLE 52. WORST CASE INDIVIDUAL DOSES IN 2000 AT 0.1 MILE

Material	Nuclide	Release (Ci)	Frequency (10^{-6} yr^{-1})	Critical Organ Dose (mrem)				
				Whole Body	Lung	GI Tract	Thyroid	
							Adult	Child
Spent Fuel	Kr-85	2.9E6	11.0	4.8E0				
	I-131	7.8E1	11.0				2.0E1	7.6E0
	FP	1.4E6	11.0	1.9E0	2.3E3	2.6E1		
Recycled Plutonium	Pu	7.8E0	0.11		1.6E5			
High-Level Solid Waste	FP	5.4E6	0.16	7.3E0	9.9E3	4.3E2		
Noble Gas	Kr-85	1.8E6	1.4	1.4E2				

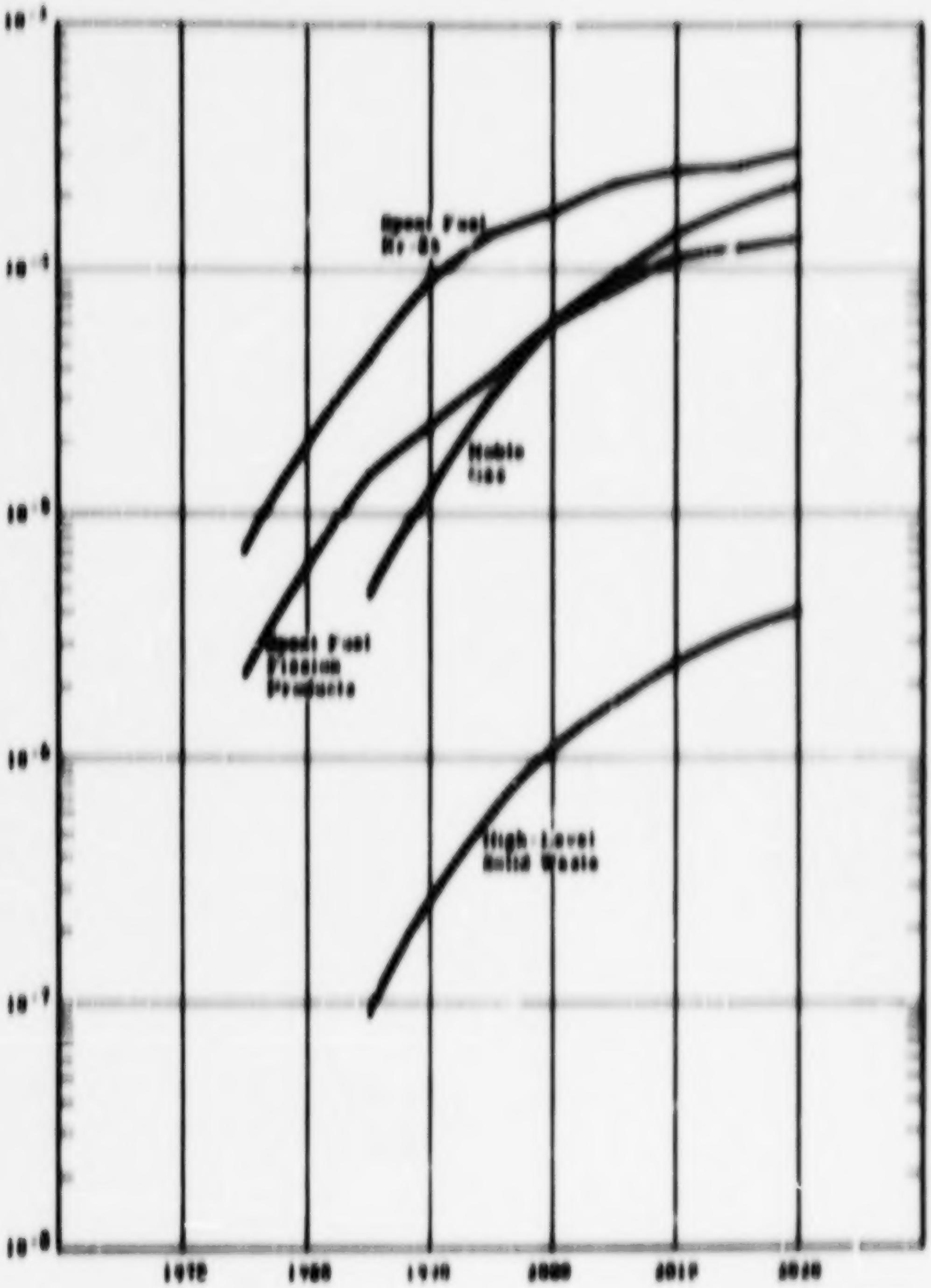

FIGURE 24. ANNUAL WHOLE BODY POPULATION DOSE

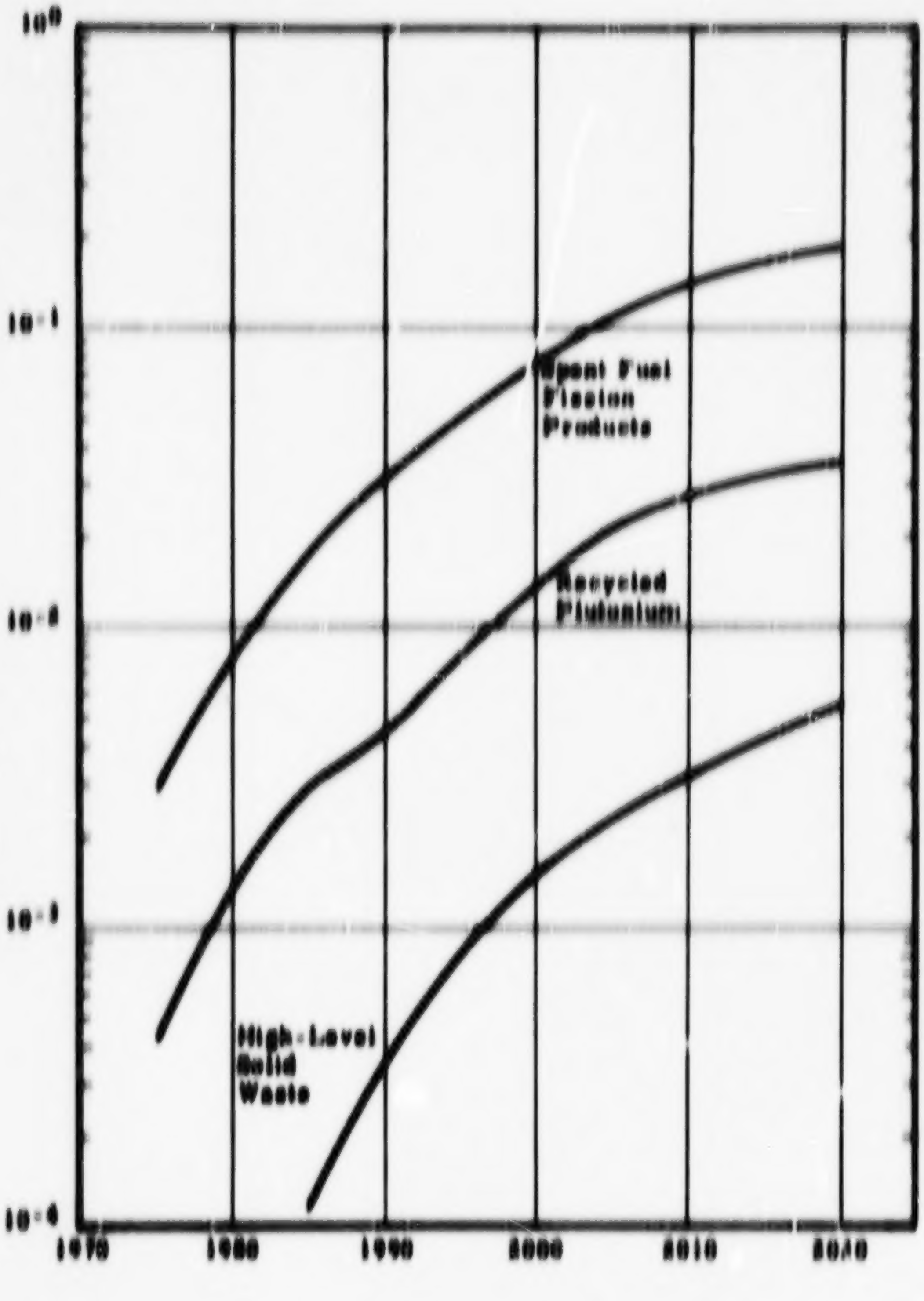

FIGURE 25. ANNUAL LUNG POPULATION DOSE

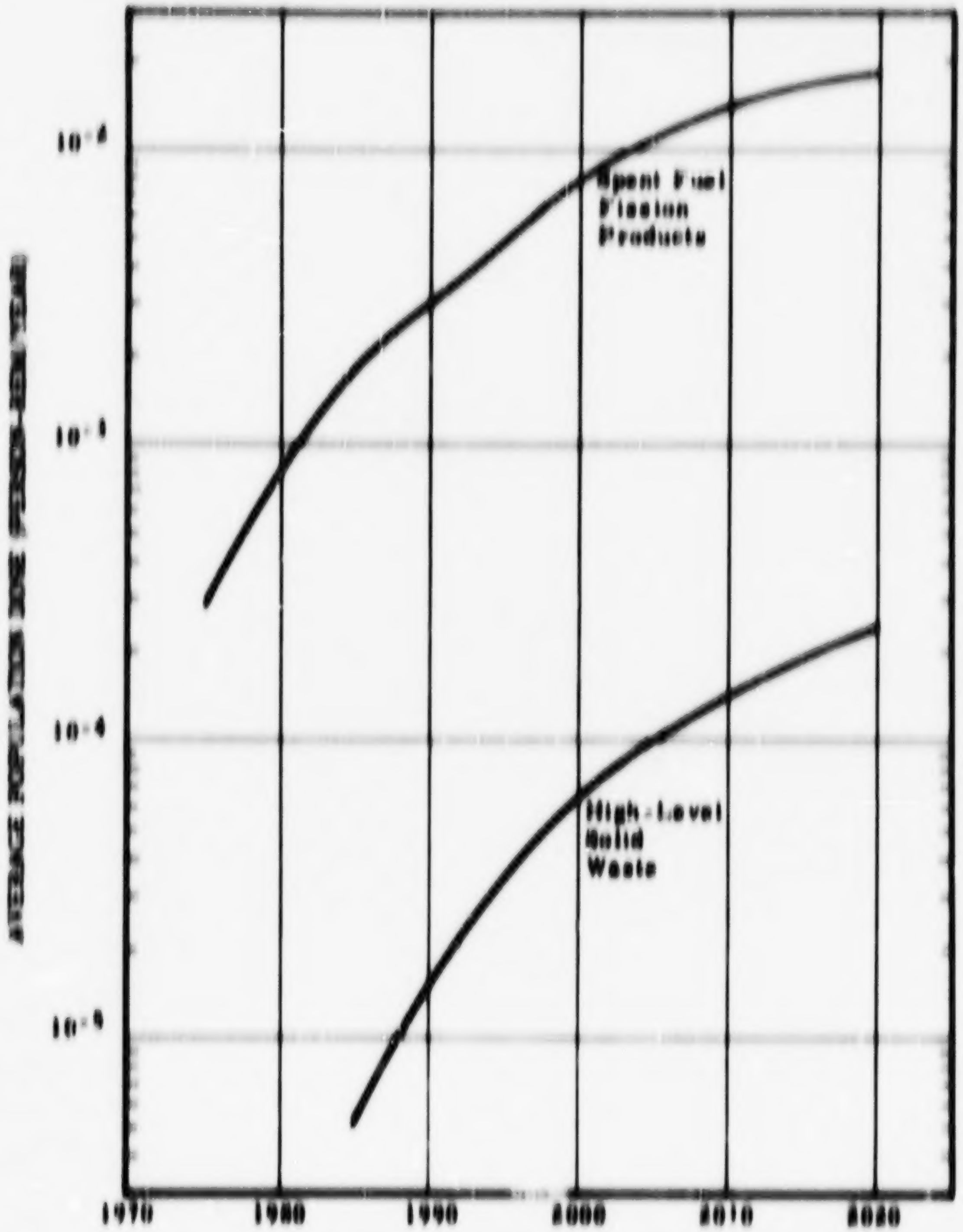

FIGURE 26. ANNUAL GI TRACT POPULATION DOSE

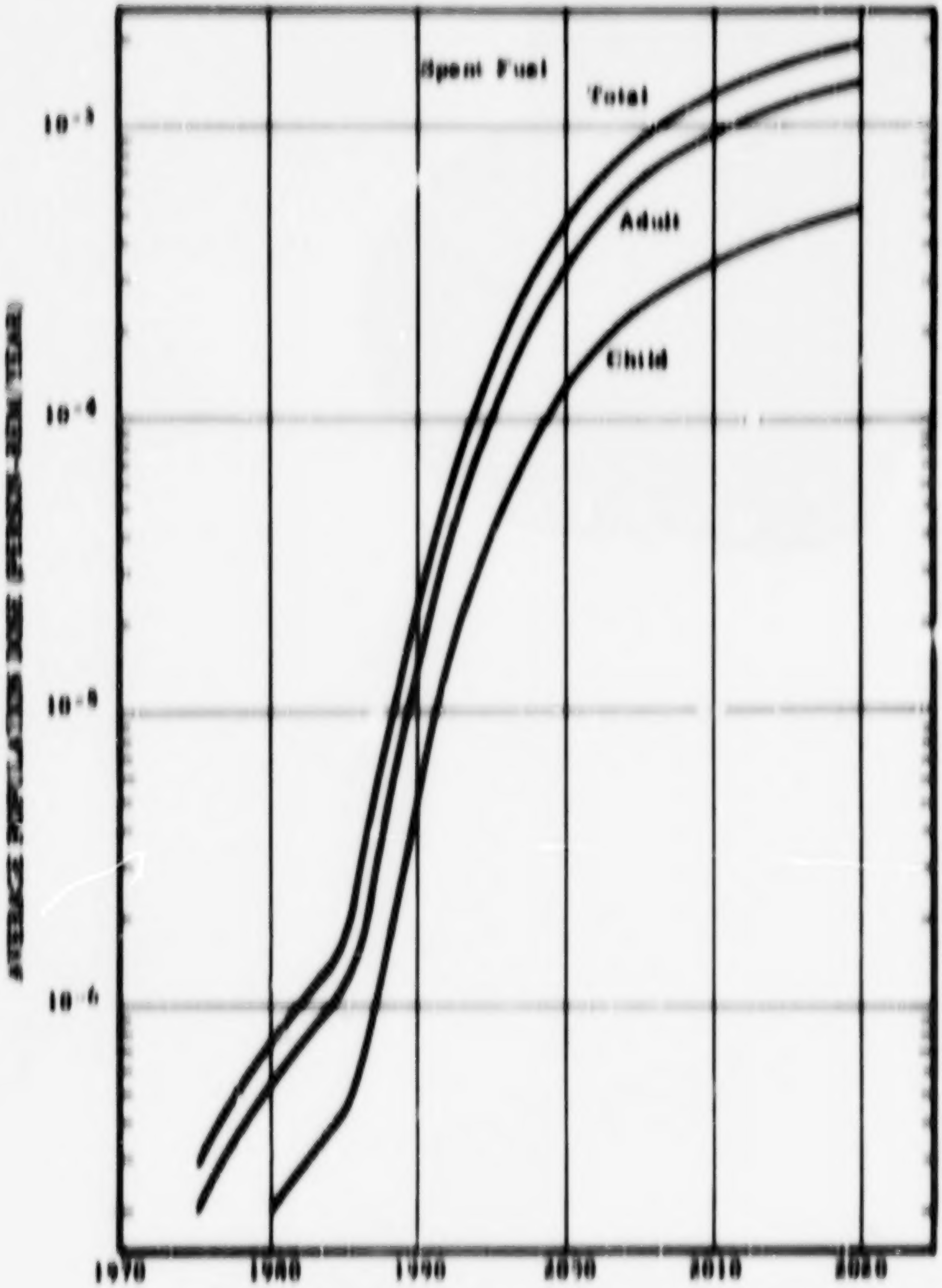

FIGURE 27. ANNUAL THYROID POPULATION DOSE

greater than average, the population dose would be proportionately higher. The probability of the higher exposure would be correspondingly less, based on the population model of Table 46. For example, there is one chance in 50 that the population dose would be ten times greater than the values presented in Figures 24 through 27; there is one chance in a thousand that the population dose would be 100 times greater.

The population doses shown in Figures 24 through 27 are annual averages corresponding to the average annual releases of radioactivity presented in Table 49. For comparison purposes, the conditional population doses in 2020 from infrequently occurring actual releases and their expected frequencies of occurrence are shown in Table 53.

HEALTH EFFECTS

None of the average annual individual doses in Table 50 exceeds the thresholds for fatalities or nonfatal effects shown in Table 47.

Of the conditional individual doses shown in Table 51, none exceeds the 50-rem threshold for acute effects from whole body exposure. The largest whole body exposure in Table 51 is 10 rem from noble gas release. In accordance with Figure 33, this exposure will occur with an average frequency of once per 14,000 years in 2020. None of the releases result in conditional individual dose to the lung, GI tract or thyroid greater than the threshold for fatalities or nonfatal effects shown in Table 47. The most significant exposures are to the lung. The maximum values shown in Table 51 are: 73 rem from spent fuel, 270 rem from plutonium and 470 rem from high-level solid waste. The largest dose to the GI tract is 21 rem from high-level solid waste. All thyroid exposures are less than one rem. The maximum exposure frequencies occur in 2020. They are: one in 20 years from spent fuel; one in 400 years from plutonium; and one in 2000 years from high-level solid waste.

The worst-case individual dose from whole body exposure shown in Table 52 is 140 rem from noble gas release with an exposure frequency of once per 700,000 years in 2020. For worst-case individual doses to the lung, GI tract or thyroid, only lung doses exceed thresholds for fatalities and nonfatal effects. The highest lung exposure (1.6 Mrem) would arise from plutonium with a frequency of occurrence in 2020 of about once in nine million years. An exposure of 9,100 rem to the lung could occur from high-level solid waste about once per seven million years in 2020. The lung exposure from spent fuel is 2,100 rem with a frequency of about once per 90 thousand years in 2020. The largest exposure to the GI tract is 430 rem from high-level solid waste.

TABLE 53. CONDITIONAL POPULATION DOSES IN 2000

Material	Nuclide	Frequency (yr^{-1})	Critical Organ Dose (person-rem)				
			Whole Body	Lung	GI Tract	Thyroid	
						Adult	Child
Spent Fuel	Kr-85	0.075	1.9E-3				
	I-131	0.075				2.5E-2	6.9E-3
	FP	0.075	1.7E-3	2.4E0	2.4E-1		
Recycled Plutonium	Pu	0.0025		1.4E1			
High-Level Solid Waste	FP	.00053	7.8E-3	1.8E2	4.5E-1		
Noble Gas	Kr-85	.00072	3.1E0				

As expected, the annual population doses increase during the entire fifty-year period. The maximum values of the population doses from Figures 24 to 27 were combined with the delayed somatic effects of radiation exposure presented in Table 48. The results are shown in Table 54. The largest health effects are from spent fuel shipments. The expected number of delayed somatic effects, both fatal and nonfatal, from population doses received from spent fuel accidents in 2020 is insignificant.

TABLE 54. DELAYED SOMATIC EFFECT OF POPULATION DOSES IN 2020

Material	Fatalities			Nonfatal Effects			
	Body	Lung	Tract	Body	Lung	Tract	Thyroid
Spent Fuel	8.1E-8	9.0E-6	5.4E-7	4.0E-8	4.5E-6	2.7E-7	8.8E-8
Recycled Plutonium		1.8E-6			9.0E-7		
High-Level Solid Waste	8.2E-10	2.7E-7	7.2E-9	4.1E-10	1.3E-7	3.6E-9	
Noble Gas	4.4E-8			2.2E-8			

SECTION IX

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